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RELIABILITY-PREDICTION PROGRAM FOR ORGANIC RANKINE-CYCLE ENGINE GENERATOR SYSTEMS

by

D.J. Hoffmann

November 1970

Prepared for
U.S. Army Mobility Equipment
Research and Development Center
under Contract DAAK01-70-D-4142-0002

ARINC Research Corporation
a Subsidiary of Aeronautical Radio, Inc.
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CAUTION

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ABSTRACT

A reliability-prediction program was conducted by ARINC Research Corporation to provide the U.S. Army Mobility Equipment Research and Development Center with quantitative reliability predictions of two manufacturers' organic Rankine-cycle engine generator systems and a computer program for calculating the predictions. Historical failure data were compiled, and a reliability-prediction mathematical model was developed. A computer program was developed, and reliability predictions were made for the two systems for a variety of missions and environments.

FOREWORD

This report was prepared by ARINC Research Corporation for the U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia, under Contract DAAK01-70-D-4142. Its purpose is to provide a quantitative reliability assessment of engine generator systems currently being developed by Fairchild Hiller, Stratos Division and Thermo Electron Corporation.

SUMMARY

INTRODUCTION

This report presents the results of a reliability-prediction program for closed organic Rankine-cycle engine generator sets. The program was conducted by ARINC Research Corporation for the U.S. Army Mobility Equipment Research and Development Center during the period July 1970 to September 1970.

The Rankine-cycle generator systems of two manufacturers — Fairchild Hiller, Stratos Division, and Thermo Electron Corporation — are considered in this report. Each is a self-contained integrally started power-generator system capable of eight hours' operation on its own fuel supply.

RELIABILITY-PREDICTION MODEL

In preparation for developing the prediction model, parameters that define the systems were specified, together with the missions and environments. The reliability block diagrams and prediction equations (mathematical model) were formulated from system functional schematics, drawings, and diagrams.

FAILURE DATA

A number of failure-rate data sources were surveyed and the failure rates for similar components listed. Operational factors required to adjust each failure rate to the environmental modes and manufacturers' estimates were derived. A Failure Mode and Effect Analysis (FMEA) was also performed.

COMPUTER PROGRAM

A computer program depicting the mathematical prediction model was prepared. This program can be exercised for any basic series-constructed system over a wide range of time. The output (reliability predictions) can be obtained for a variety of mission types over four operating environments. The program was made sufficiently flexible to allow system-configuration changes, as well as failure-rate distributions other than the assumed constant failure rate.

FLUIDIC-CONTROL APPLICATION

The feasibility of utilizing fluidic control devices was investigated briefly. The advantages and disadvantages of such devices, their estimated reliability, and areas of application were evaluated.

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ILLUSTRATIONS AND TABLES

CHAPTER ONE

INTRODUCTION

Under Contract DAAK01-70-D-4142 to the U.S. Army Mobility Equipment Command, ARINC Research Corporation assessed the relative effectiveness of two organic Rankine-cycle power plants under development for the Electrotechnology Laboratory at the U.S. Army Mobility Equipment Research and Development Center (USAMERDC).

The purpose of the assessment was to make quantitative reliability predictions for the two candidate configurations and to provide USAMERDC with the basic tools for performing future reliability analyses. A hypothetical system with idealized characteristics was used to show the ultimate reliability of the Rankine-cycle power plant. The following tasks were performed:

- Review available information on the Rankine-cycle power plants and establish baseline data
- Identify a representative mission and define system failure
- Perform a Failure Mode and Effect Analysis
- Develop a reliability-prediction model at the major-component level sufficiently flexible to permit configuration changes and the use of various types of failure distributions
- Perform a reliability prediction of the two candidate systems and a hypothetical system
- Develop an estimate of the mean active-repair times for the candidate systems and determine the availability of the systems

This report presents a background discussion and description of the candidate systems, Failure Mode and Effect Analyses for the systems, the prediction model and the predictions themselves, and a discussion of the application of fluidic controls to the Rankine-cycle engine. The conclusions and recommendations resulting from the study are also presented.

CHAPTER TWO

BACKGROUND

The U.S. Army is currently conducting a technical evaluation of silent ground-power systems. The Rankine-cycle engine is one of the candidate prime movers for such a system. Two contracts to develop a Rankine-cycle engine generator set were awarded by the U.S Army Mobility Equipment Research and Development Center (USAMERDC), Ft. Belvoir, Virginia, to Fairchild Hiller Stratos Division, Bay Shore, New York, and Thermo Electron Corporation, Waltham, Massachusetts.

The closed Rankine cycle for steam or organic working fluids involves the four thermodynamic processes shown in the pressure-volume (PV) and temperature-entropy (TS) diagrams of Figure 1.

Ideally, the working fluid undergoes an isothermal and isentropic pressure increase in the feed pump, process 1—2; and a temperature increase in the boiler at constant pressure, saturating, evaporating, and superheating the fluid, process 2—3. Process 3—4 represents an isentropic pressure decrease in the engine; and process 4—1 is the constant-pressure heat transfer in the condenser, condensing the vapor back to a liquid to re-enter the feed pump.

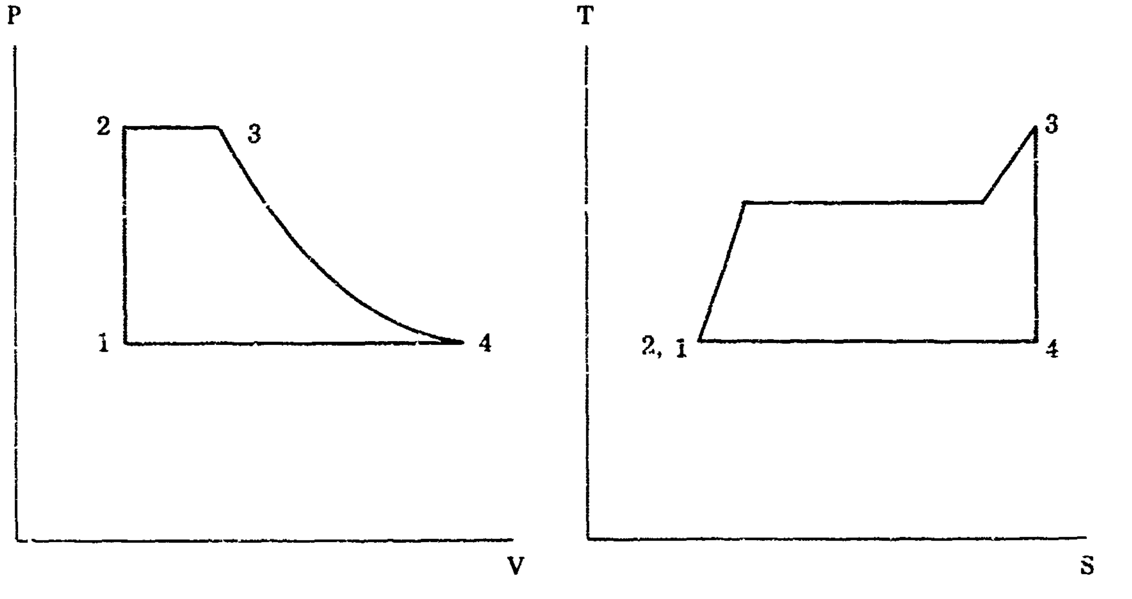

Figure 1. RANKINE CYCLE PV AND TS DIAGRAMS

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The organic Rankine-cycle systems have a potential problem area with the organic fluids. If overheated, the fluids undergo thermal decomposition, rendering the system useless.

Figure 2 is a flow schematic for a basic Rankine-cycle engine generator set that uses an organic fluid as the working substance. The numbers correspond to the processes in the cycle. The regenerator is used to increase the efficiency of an organic Rankine cycle. The energy of the superheated exhaust vapor is transferred internally in the cycle to the working fluid after the fluid leaves the feed pump; this significantly reduces the energy required to vaporize or superheat the fluid in the boiler.

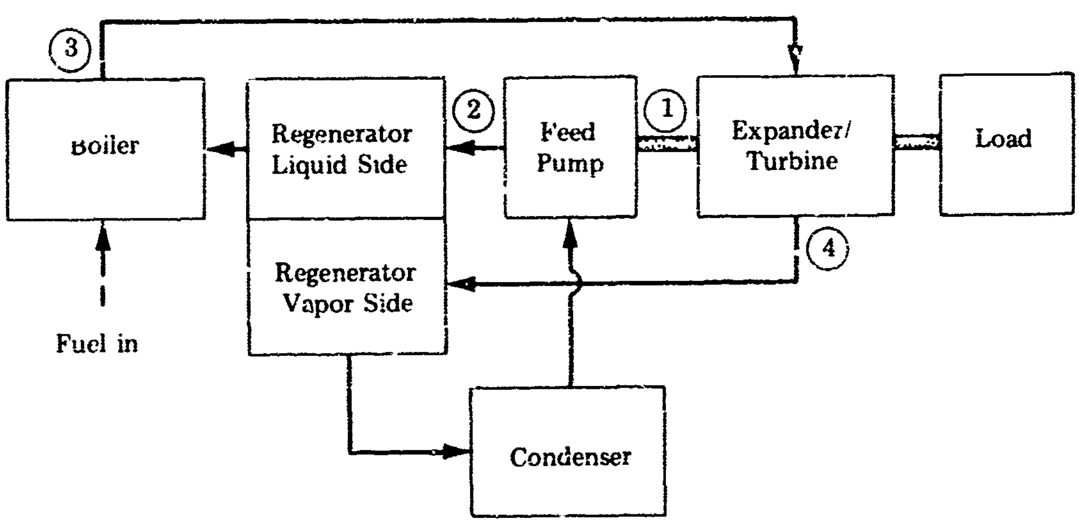


Figure 2. BASIC FLOW SCHEMATIC FOR ORGANIC RANKINE-CYCLE SYSTEM

CHAPTER THREE

RELIABILITY-PREDICTION MODEL

The term "reliability-prediction model" describes the block diagrams and equations that depict and mathematically relate component reliabilities to overall system reliability. The development of a reliability-prediction model encompasses several tasks:

- Definition of the system mission
- Definition of system failure
- Statement of assumptions
- Development of reliability block diagrams
- Development of reliability-prediction equations

3.1 SYSTEM DEFINITIONS

The two manufacturers' systems are similar. The major difference that might affect reliability is in the power output level of the generator sets, which affects set size. The following system descriptions show the differences between the manufacturers' designs.

3.1.1 Fairchild Hiller, Stratos Division System

Fairchild Hiller Stratos Division, hereinafter called STRATOS, is designing a 1.5-kW organic Rankine-cycle engine generator set rated at 28 Vdc. The set will be inaudible at 100 meters, will weigh approximately 150 pounds, and will measure approximately 2′ × 2′ × 2′.

Figure 3 is a flow schematic of the STRATOS generator set. The organic working fluid is FC75. To protect against overheating or overpressurization, a thermal sensor is placed at the fluid exit point on the boiler to shut the system down. A pressure-burst disc is also placed in the fluid loop for additional protection of the system components in case the thermal sensor fails and the system becomes overpressurized to the point of catastrophic line or component rupture.

The turbo alternator pump is the unique component in the STRATOS generator set. It combines three components into one on a single rotating shaft. The two fluid-film journal bearings and a thrust bearing are lubricated by the working fluid. The unit is hermetically sealed in the fluid loop, two fluid drains in the alternator case remove entrapped FC75. Liquid FC75 flows in a coil around the alternator portion of the turbo alternator pump to cool the windings. The power-conditioning circuits are mounted on a cooling plate for the same purpose. This keeps all of the major power-producing elements at a constant temperature during system operation.

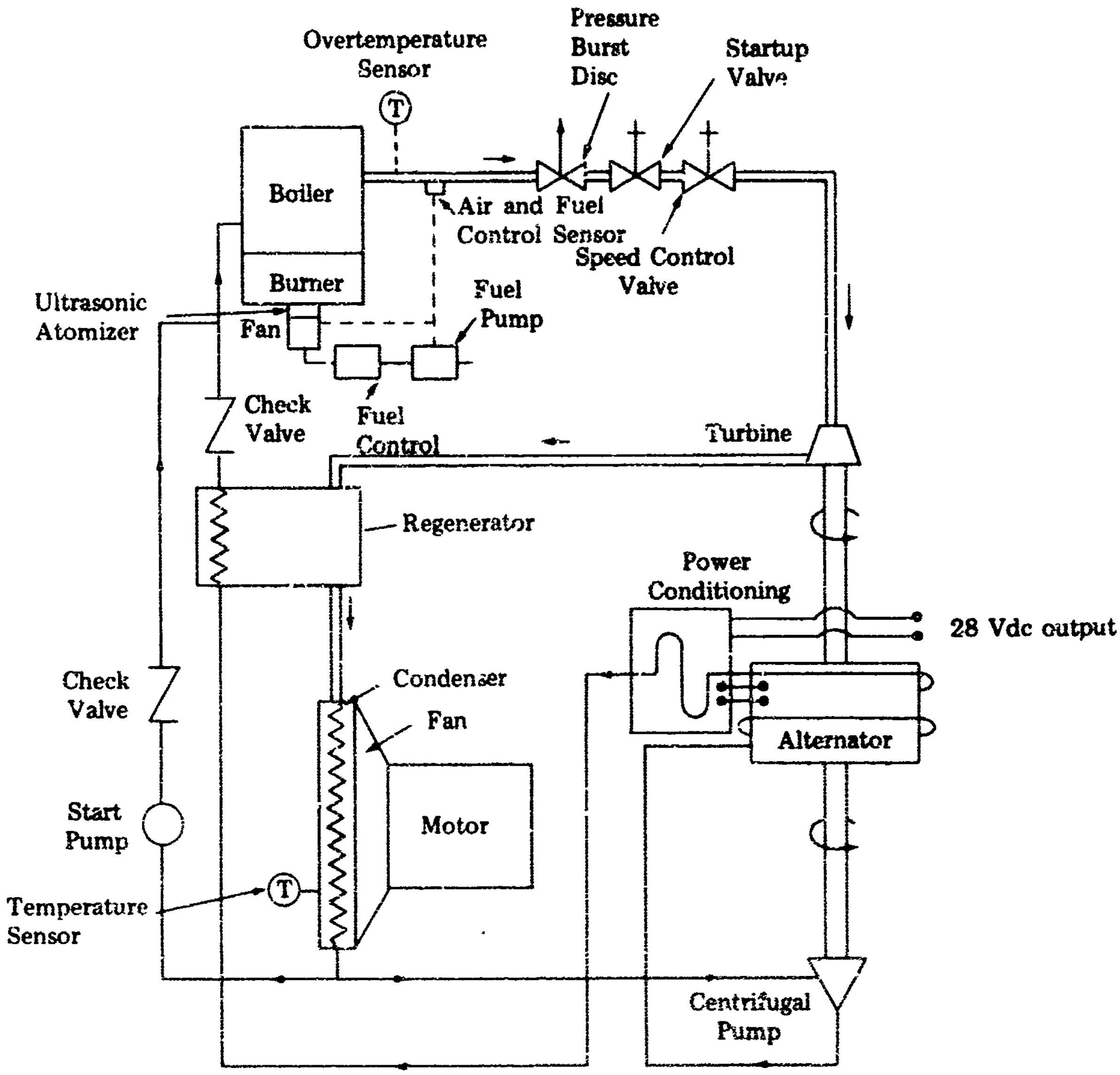


Figure 3. **STRATOS ENGINE GENERATOR SET**

The condenser fan and the fuel pump are driven by variable-speed motors. The motor speeds are adjusted by thermal sensing circuits to maintain constant fluid-loop conditions.

The alternator speed is kept constant by a solenoid modulation valve in the fluid loop just prior to the turbine inlet. The valve is controlled by a circuit that detects the output of the alternator and sends a signal to the solenoid to vary the flow rate to the turbine. The feed pump is a centrifugal noncavitating pump whose output is kept constant by the alternator's fixed RPM.

The fluid loop is hermetically sealed. It is therefore repairable only at the depot level. Most support components in the systems (see Chapter Two) are repairable at the organizational level of maintenance. The electrical and electronic circuits are currently planned to be field- or depot-repairable.

3.1.2 Thermo Electron Corporation System

Thermo Electron Corporation, hereinafter called TECO, is designing a 3-kW, 120-Vac Rankine-cycle generator set. It will be inaudible at 100 meters, weigh approximately 300 pounds, and measure approximately 2.5' × 2.5' × 2.5'. Figure 4 is a functional schematic of the TECO generator set.

CP34, an organic substance, is used as the working fluid. To protect against overpressure or temperature, safety sensors are placed in the fluid loop. The boiler requires a buffer fluid around the organic fluid because of the extreme temperatures. The buffer fluid transfers the thermal energy to the working fluid. The flow energy of the vapor is converted to rotary motion in a reciprocating two-cylinder engine that is coupled to the alternator. The vapor is then exhausted through the regenerator to the condenser. A positive-displacement piston feed pump is gear-driven off the engine; it is located upside-down to form the bottom of the engine crankcase. The crankcase is filled with a silicone lubricant to lubricate both the engine and the feed pump. The silicone is miscible with the CP34; a fluid/lubricant separator is thus necessary in the loop since the seals and rings in the engine and feed pump are not 100-percent leakproof.

When the system is not in use, the working fluid and lubricant characteristically migrate to the engine crankcase. A starting fluid reservoir is placed in the loop to drain the accumulated fluid from the engine. This reservoir provides the fluid to the start pump, preventing pump cavitation at system startup.

A motor-driven throttle valve is used to maintain constant engine speed. Alternator output is sensed by a speed-control circuit, and a control signal is sent to the valve's driving motor.

The fluid loop is hermetically sealed, except for the shaft seal on the engine crankshaft which must penetrate the crankcase to connect to the alternator, making it extremely impractical for the user or field-support maintenance facilities to repair components in the loop. Most of the electrical and electronic components, fuel- and air-supply components, and condenser fan are planned to be field-repairable.

3.2 SYSTEM MISSIONS

The U.S. Army Mobility Equipment Research and Development Center has established a goal of a 95-percent reliability for the generator sets, with a confidence level of 90

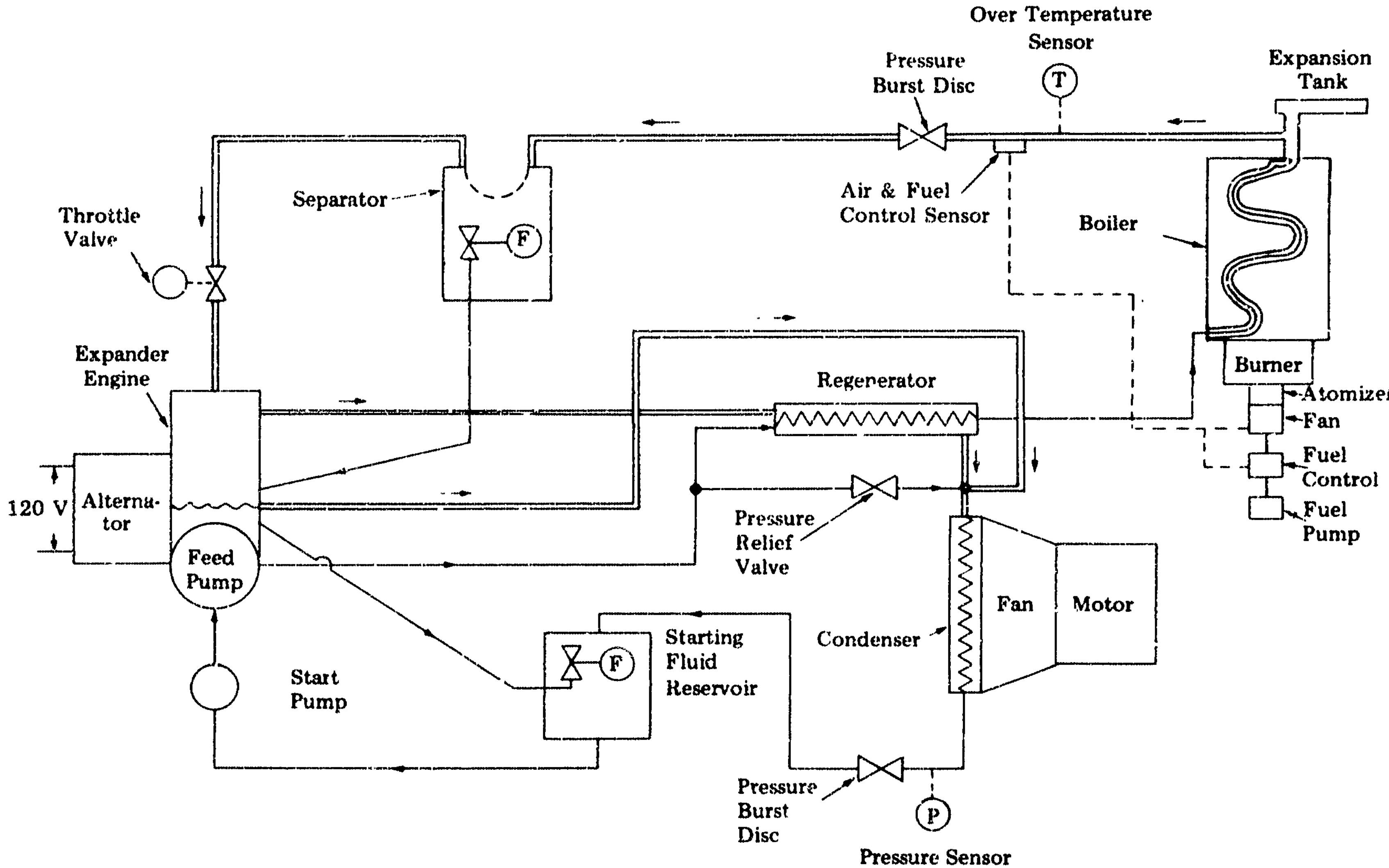


Figure 4. **TECO ENGINE GENERATOR SET**

percent, for a mission duration of 24 hours and an inherent availability of 98 percent. ARINC Research Corporation used this requirement as a basis for developing two representative missions.

3.2.1 Mission Profile

3.2.1.1 Mission I

The first mission is for the Rankine-cycle generator set to start up in three minutes (0.05 hour) and continuously deliver power for 24 hours without shutting down. It is connected to an external fuel tank, but this fuel source is not considered in the reliability model.

3.2.1.2 Mission II

The second mission involves cycling the generator set through startup and power delivery four times in 100 hours. Two of the startups are hard starts, requiring six minutes (0.1 hour) each; the other two starts require the normal three minutes. The sets deliver power continuously for 25 hours after each start.

3.2.2 Environments

At the beginning of the project it was planned to incorporate the effects of temperature and weather conditions as the environmental effects on the system. It became apparent, however, that there was little operational information on mechanical and electromechanical equipment that reflected these environmental factors. Data were available on several operating applications for these equipments; the three of these which were used are described below.

3.2.2.1 Portable Ground Environment

The generator set is in a portable condition, not rigidly mounted in a fixed installation; it can be moved from place to place in vehicles traveling over unimproved roads and can be loaded and unloaded manually.

3.2.2.2 Tracked-Vehicle Environment

The generator set is mounted on a tracked vehicle capable of traveling over open terrain. The set is subject to severe shock and vibration in transport. The sets will normally be operated while the vehicle is not moving, although operation is not restricted to times when the vehicle is stationary.

3.2.2.3 Laboratory Environment (Hypothetical System With Idealized Characteristics)

The laboratory environment was used to meet the contract requirement to develop a prediction for a hypothetical system with idealized characteristics. The laboratory conditions are based on the assumption that the sets are functioning in an ideal environment with skilled personnel performing the operational tests. It is believed that the data produced under these conditions show the best achievable reliability for the prototype models and indicate what can be expected from production units in the field that are superior in design and reliability to the prototype generator sets. The system manufacturers currently believe that the best method to achieve higher system reliability is to improve the design rather than incorporate redundancy.

3.3 FAILURE DEFINITIONS

The loss of any critical component that prevents the generator system from meeting 100-percent power-output capability results in system failure. A critical component is any item or part whose failure would preclude successful operation of the system or create safety hazards. Included in this category are the components required for starting the system since without starting capability power output cannot be achieved.

Failure of any safety-shutdown circuit is a system failure. These circuits are fail-safe — that is, the loss of one of them will automatically shut down the system.

3.4 ASSUMPTIONS

After the systems, the missions, and failure were defined, the following major assumptions were made to establish prediction-model limitations:

- Once the system has exceeded the infant-mortality period, the failure rate does not change during the life of the system (exponential distribution).
- All components must function properly at the prescribed time in the mission for complete system success.
- System safety-shutdown circuits are not fail-safe.
- Generator-set maintenance will not include any components in the fluid loop, because the loop is hermetically sealed by the manufacturer or depot.

3.5 RELIABILITY BLOCK DIAGRAMS

A reliability block diagram is a pictorial chart of a system or subsystem that depicts the interactions between the components of the system and the effects of a component failure on the system.

Figure 5 is the reliability block diagram for an organic Rankine-cycle engine generator system composed of four functional groups or subsystems:

- **Fluid-Loop Group** — any component that comes into direct active contact with the organic fluid
- **Power-Generation Group** — the components and circuits that make up the power-generation, -conditioning, and -rectifying segment of the generator sets (excluding the alternator in the STRATOS system, which is included in the fluid-loop group because it is hermetically sealed in the loop)
- **Electronic Control Circuits Group** — the circuits that control, regulate, and protect the generator set, along with the electronic or electrical sensors providing the proper input signals
- **Support-Components Group** — components or items that do not directly fall into the other three groups and provide a supporting service to the end mission of the generator set

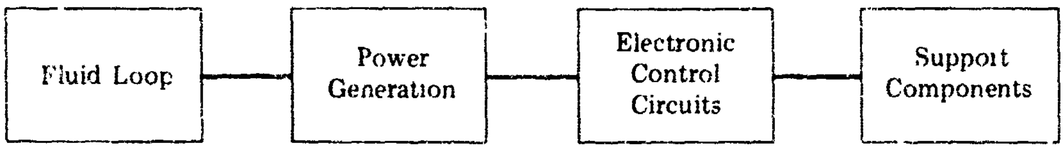


Figure 5 **RELIABILITY BLOCK DIAGRAM, ORGANIC RANKINE-CYCLE ENGINE GENERATOR SYSTEM**

Figures 6 and 7 are the functional-group reliability block diagrams for the STRATOS and TECO systems, respectively. A five-digit code is assigned to every block in the reliability diagrams for identification in the computer mathematical model when failure distributions are being inputted. Whenever a change is made in the diagram, it is necessary to add or subtract a code depending on whether a component is added or removed.

3.6 RELIABILITY-PREDICTION EQUATION

The reliability-prediction equation expresses the mathematical relationships between the system components in the reliability block diagram, showing how they are related to overall system reliability.

The Rankine-system components have basically a direct series relationship. The computer model calculates the reliabilities of all the components individually. The failure distribution of each component or circuit, the amount of accrued operating time on the component, and whether or not the component is a redundant element in the overall model are required for these calculations. These data are inputted into the model with the component's five-digit identification number (see Chapter Six).

The series model for either generator system composed of n elements can be simply expressed as

$$R_s = \prod_{i=1}^{n} R_{i(t)} = R_1 \cdot R_2 \cdot R_3 \cdots R_n$$

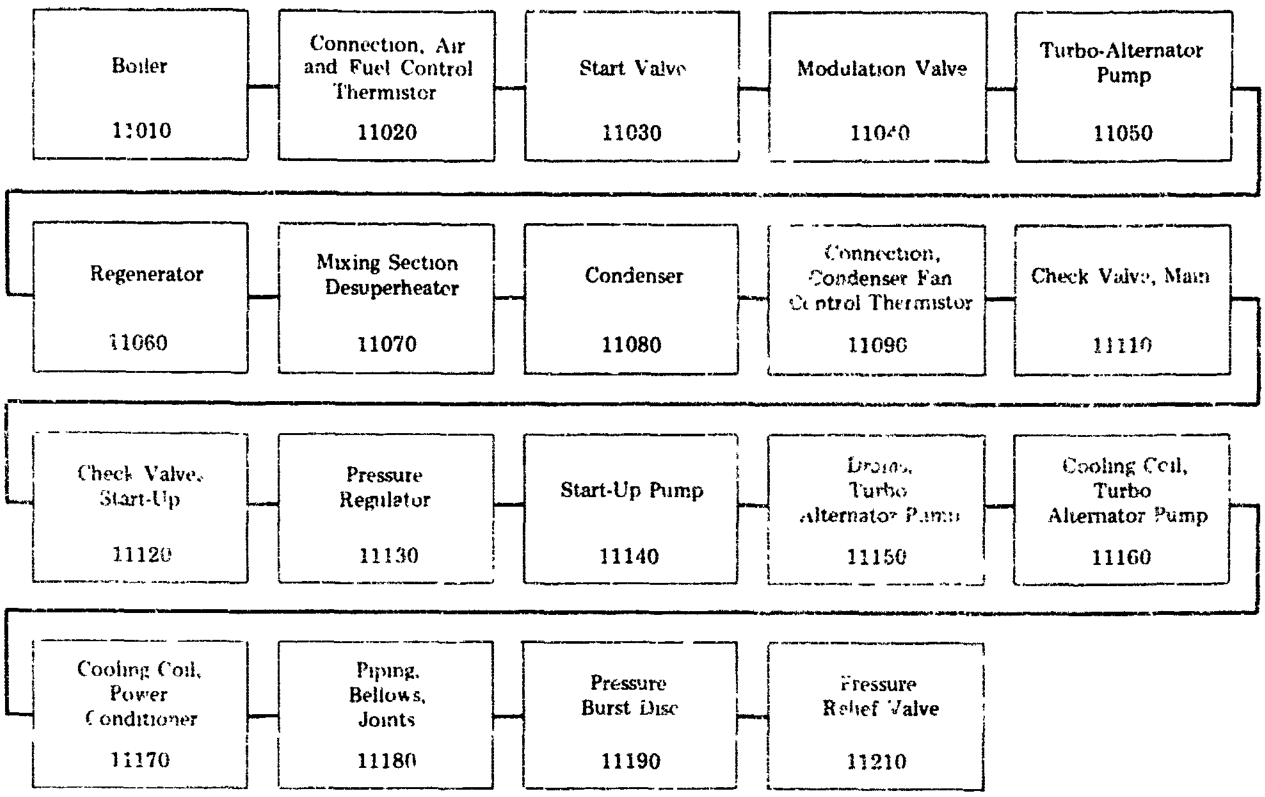
The equations for calculating the reliabilities from the four distributions used in this study for any single component are as follows:

Exponential

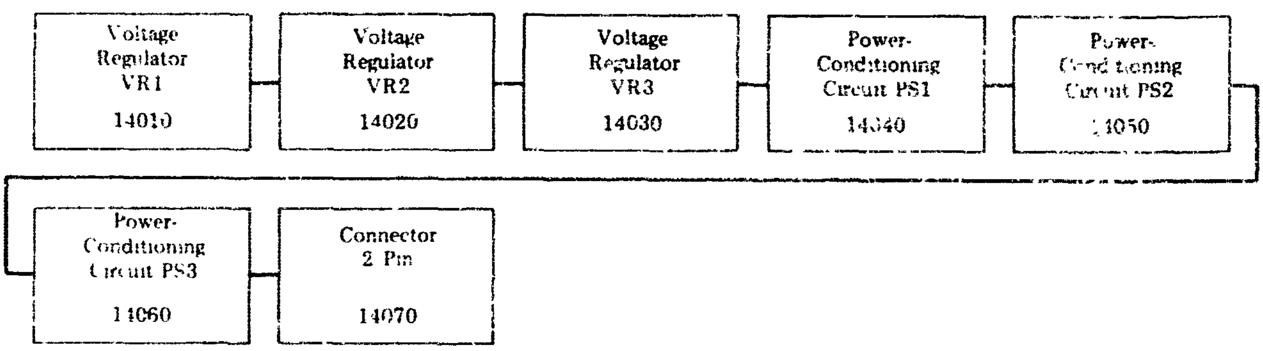
$$R_i(t) = e^{-\lambda_i t}$$

Normal

$$R_i(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\theta)^2}{2\sigma^2}} dt$$

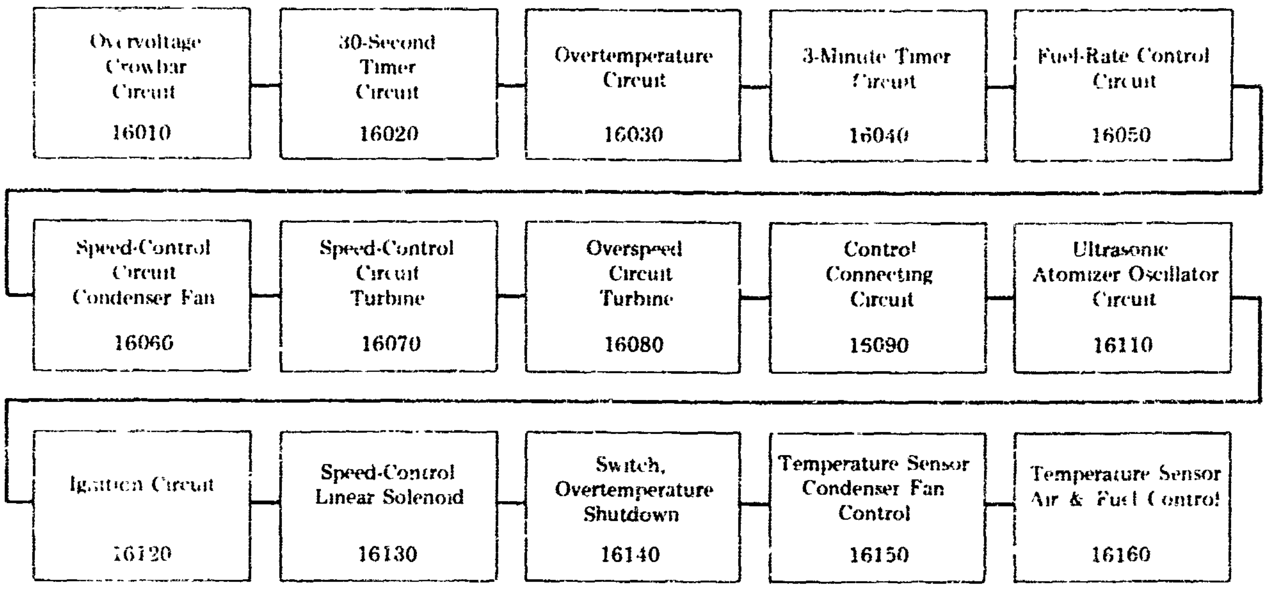


(a) Fluid Loop, 11000

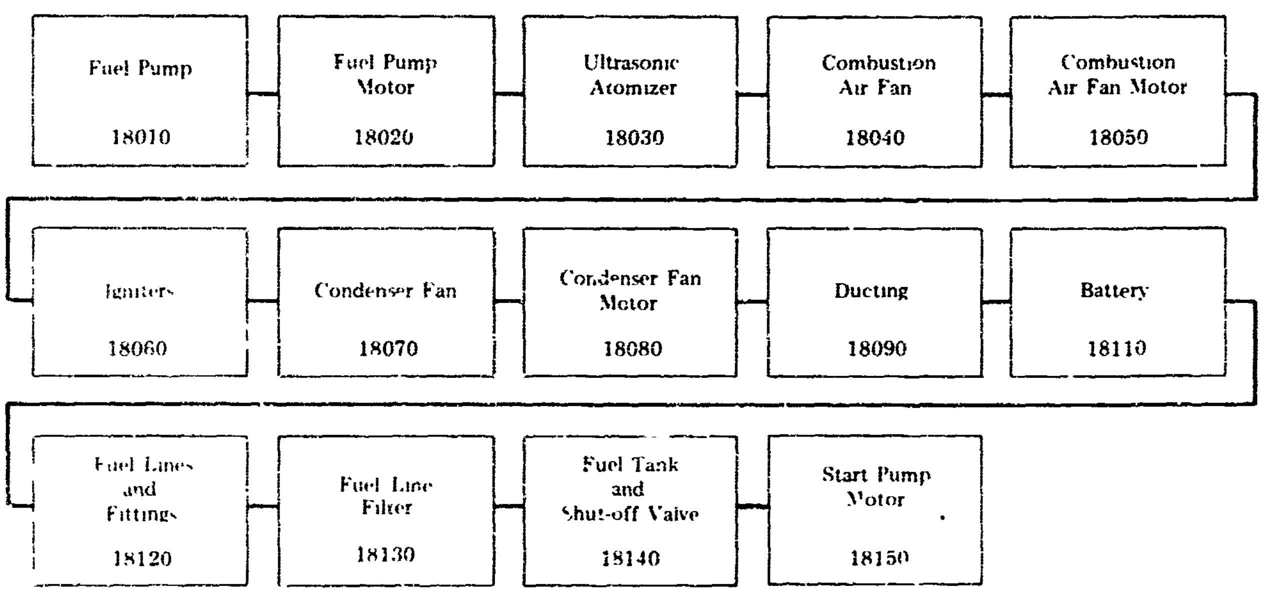


(b) Power Generation, 14000

Figure 6 FUNCTIONAL-GROUP RELIABILITY BLOCK DIAGRAMS FOR STRATOS SYSTEM



(c) Electronic Control Circuits, 16000



(d) Support Components, 18000

Figure 6 (continued)

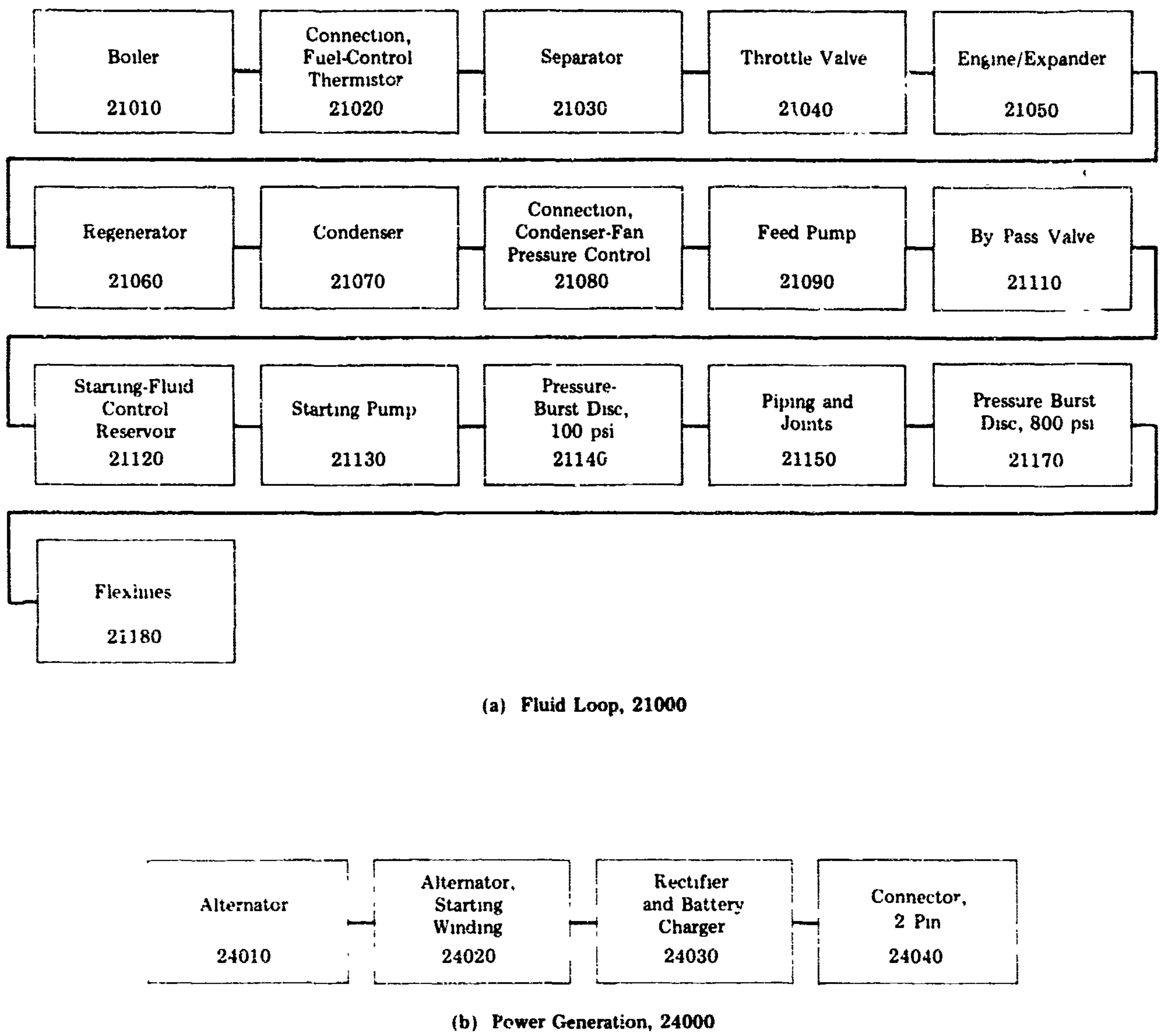
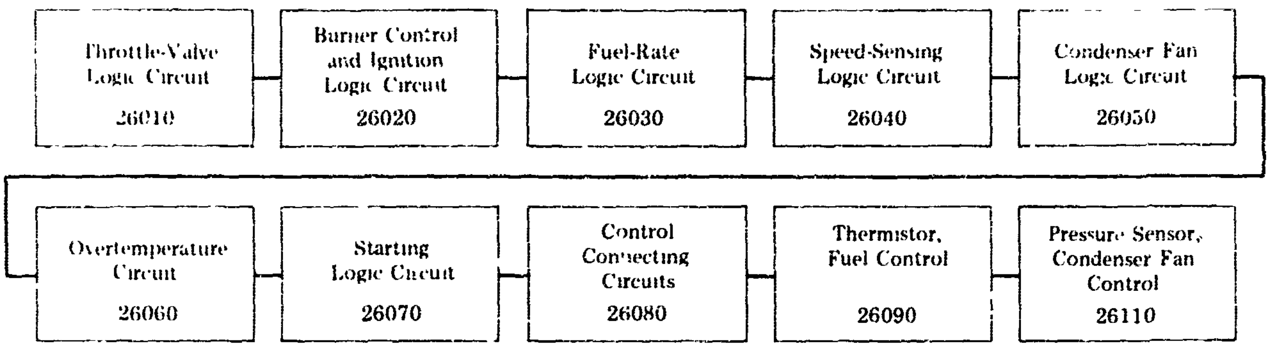
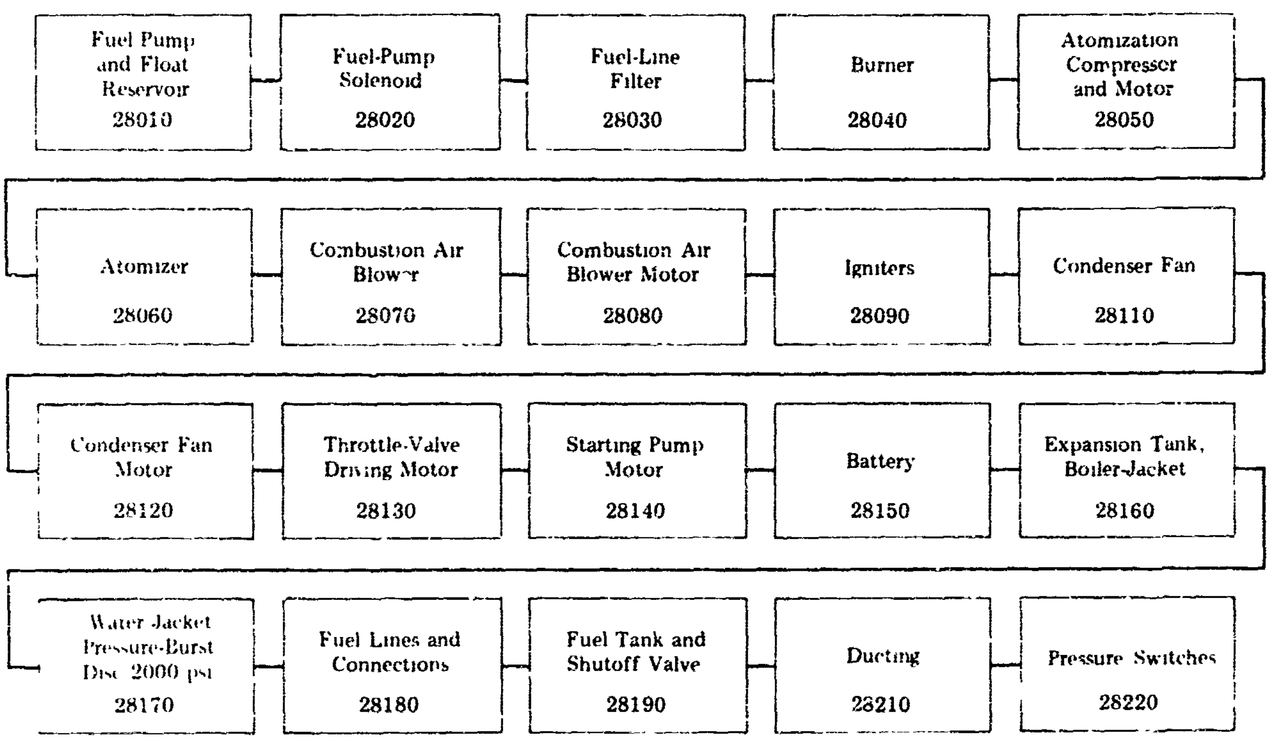


Figure 7. **FUNCTIONAL-GROUP RELIABILITY BLOCK DIAGRAMS FOR TECO SYSTEM**



(c) Electronic Control Circuits, 26000



(d) Support Components, 28000

Figure 7 (continued)

Log Normal

$$R_i(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \frac{1}{t} e^{-\frac{(\ell n\, \theta t)^2}{2\sigma^2}} dt$$

Probability

$R_i(t)$ = Probability of success

It was necessary to use exponential data for the predictions. However, during prototype testing and development testing, with the proper data-collection techniques and sufficient test time, it will be possible to develop the true failure distributions for each component.

CHAPTER FOUR

DATA COLLECTION

4.1 DEVELOPMENT OF EQUIPMENT FAILURE RATES

Since operational data were not available for most of the components in the two systems, it was necessary to research a number of failure-data sources to obtain data on similar components. The primary sources are Government and contractor data banks, which offer failure histories for a variety of mechanical, electrical, and electronic components. The sources used for this study are listed in Appendix A.

To obtain appropriate component failure rates, all the available failure rates from the data sources used were listed and then screened for a best-fit average failure rate in a known environmental condition. The environmental conditions for the data ranged from the laboratory to space vehicles. Tables 1 and 2 present component failure rates for the two Rankine-cycle generator systems. It is emphasized that all of the failure rates are exponentially distributed.

It was assumed that a portable generator set would not be subject to a single environment; therefore, three K factors were developed from the data sources. The fourth K factor is not environmentally oriented but simply adjusts the failure rate listed in the table to that developed by the manufacturer. It is thus possible to show the manufacturers' estimated reliability in comparison with the three environmental categories described in Chapter Three. The K factors are as follows:

K_1 — Manufacturer Adjusting Factor

K_2 — Portable-Ground-Environment Factor

K_3 — Track-Vehicle-Mounted Factor

K_4 — Laboratory (Hypothetical System) Factor

It is apparent from the tables that there are numerous adjusting K factors for each environmental condition. The reason for this is that different data sources were used and there is no universal factor for all equipments. The failure rates of most equipments increase as shock and vibration increase; thus a higher multiplying K factor is required for the tracked-vehicle environment to increase the average failure rate.

There are very few failure data on mechanical equipments that show the effects of extreme cold or heat on operating life. Temperature effects were therefore not considered in the environmental conditions.

The delivery of the manufacturer's prototype system to USAMERDC for operational testing is the ideal time to begin a data-collection program. There is very little operational information on organic Rankine-cycle systems; to perform a complete evaluation of the

Table 1 COMPONENT FAILURE DATA, STRATOS ENGINE GENERATOR SET

Group Block Number	Component Name	Failures Per Million Hours	K_1	K_2	K_3	K_4	Data Source
11010	Heater, Boiler	4.0	5.63	10.0	25.0	1.0	2
11020	Connection, Thermistor, Fuel Control	0.03	0.0	10.0	25.0	1.0	2
11030	Start Valve	6.88	1.89	10.0	25.0	1.0	2
11040	Modulation Valve	8.5	0.0	10.0	25.0	1.0	2
11050	Turbo Alternator Pump	24.2	2.48	1.0	2.5	0.2	2
11060	Regenerator	4.2	3.81	10.0	25.0	1.0	2
11070	Mixing-Section Desuperheater	4.6	0.0	10.0	25.0	1.0	2
11080	Condenser	5.33	3.57	10.0	25.0	1.0	1
11090	Connection, Thermistor, Condenser Fan Control	0.03	0.0	10.0	25.0	1.0	2
11110	Check Valve, Main	5.0	0.0	10.0	25.0	1.0	2
11120	Check Valve, Startup	5.0	0.0	10.0	25.0	1.0	2
11130	Pressure Regulator	2.14	0.0	10.0	25.0	1.0	2
11140	Start Pump	3.4	1.325	1.0	2.5	0.2	1
11150	Drains, Turbo Alternator, Pump (2)	0.03	0.0	1.0	2.5	0.2	2
11160	Cooling Coil, Turbo Alternator Pump	1.65	0.0	1.0	2.5	0.2	1
11170	Cooling Plate, Power Conditioning	1.65	0.0	1.0	2.5	0.2	1
11180	Lines and Fittings (40)	2.0	0.0	10.0	25.0	1.0	2
11190	Pressure-Burst Disk	0.6	0.0	1.0	1.5	0.2	1
11210	Pressure Relief Valve	17.7	0.0	1.0	2.5	0.1	1
14010	Voltage Regulator 1	32.805	1.0	2.0	10.0	0.1	5
14020	Voltage Regulator 2	29.878	1.0	2.0	10.0	0.1	5
14030	Voltage Regulator 3	3.507	1.0	2.0	10.0	0.1	5
14040	Power-Conditioning Circuit 1	11.283	1.0	2.0	10.0	0.1	5
14050	Power-Conditioning Circuit 2	0.2	1.0	2.0	10.0	0.1	5
14060	Power-Conditioning Circuit 3	0.075	1.0	2.0	10.0	0.1	5
14070	Connector, 2 Pin (Female)	0.1	1.0	1.1	5.0	0.1	4
16010	Overvoltage Crowbar Circuit	2.0	1.0	1.0	6.0	0.25	4
16020	30-Second Timer Circuit	14.3	0.175	1.0	7.75	0.175	4
16030	Overtemperature Circuit	14.3	0.14	1.0	7.75	0.145	4
16040	3 Minute Timer Circuit	50.0	0.3	1.0	5.0	0.3	4
16050	Fuel Rate Control Circuit	83.3	0.24	1.0	7.5	0.24	4
16060	Speed-Control Circuit, Condenser Fan	83.3	0.24	1.0	7.5	0.24	4
16070	Speed-Control Circuit, Turbine	85.3	0.24	1.0	7.5	0.24	4
16080	Overspeed Circuit, Turbine	83.3	0.24	1.0	7.5	0.24	4
16090	Control Connecting Circuit	25.6	0.94	1.0	6.67	0.25	4
16110	Ultrasonic Oscillator Circuit	50.0	0.3	1.0	5.0	0.3	4
16120	Ignition Circuit	25.0	0.52	1.0	6.67	0.52	4
16130	Speed-Control Linear Solenoid	6.0	1.0	1.0	1.5	0.24	4
16140	Switch, Overtemperature Shutdown	2.10	2.48	1.0	2.5	0.1	3
16150	Temperature Sensor, Fuel Control	6.0	0.83	1.0	2.5	0.2	3
16160	Temperature Sensor, Condenser Fan Control	0.3	0.0	10.0	25.0	1.0	3
18010	Fuel Pump	4.94	1.72	1.0	2.5	0.23	1
18020	Fuel Pump Motor	0.3	0.0	10.0	25.0	1.0	2
18030	Atomizer	40.5	2.4	1.0	1.0	0.1	1
18040	Fan, Air Flow	3.3	2.57	1.0	1.75	0.1	1
18050	Fan Motor, Air Flow	0.2	0.0	10.0	25.0	1.0	2
18060	Igniters (2)	3.62	0.0	1.0	6.0	0.05	1
18070	Fan, Condenser	6.6	2.36	1.0	2.5	0.1	1
18080	Fan Motor, Condenser	9.1	0.0	1.0	2.5	0.1	1
18090	Ducting	12.46	0.0	1.0	2.5	0.75	1
18110	Battery	9.1	0.0	1.0	2.5	0.2	1
18120	Lines and Fittings, Fuel	1.2	0.0	10.0	25.0	1.0	2
18130	Fuel Filter	0.3	0.0	10.0	25.0	1.0	2
18140	Fuel Tank and Shutoff Valve	20.1	0.0	1.0	2.5	0.1	1
18150	Start Pump Motor	20.1	0.0	1.0	1.5	0.5	1

n = 55 (total number of components)

DATA SOURCE
(1) FARADA
(2) Mechanical Design and Systems Handbook
(3) Apollo Reliability Prediction Estimation and Evaluation Guidelines
(4) MIL-HDBK-217A
(5) Manufacturer

Table 2 COMPONENT FAILURE DATA, TECO ENGINE GENERATOR SET

Group Block Number	Component Name	Failures Per Million Hours	K_1	K_2	K_3	K_4	Data Source
21010	Boiler	4 9	1.02	8 0	22 0	1 0	3
21020	Connection Thermistor, Fuel Control	0 03	0 0	10.0	25 0	1.0	2
21030	Separator	1.30	3.46	8 0	22 0	1 0	1
21040	Throttle Valve	21 3	1 65	1.0	2 0	0 83	1
21050	Engine, Expander	31 6	0 475	1.0	2.24	0 275	1
21060	Regenerator	4 20	0 595	10 0	25.0	1.0	2
21070	Condenser	5 33	1 3	10.0	25 0	1 0	1
21080	Connection, Pressure Sensor, Condenser Fan Control	0 02	0 0	10 0	25 0	1 0	2
21090	Feed Pump	36.5	0.274	1 0	1.37	0.334	1
21110	Pressure-Control Valve	5.92	2 04	8 0	22 0	1.0	3
21120	Starting-Fluid Reservoir	24 3	0 1975	1 0	2.83	0 1	1
21130	Start Pump	3 4	1 38	1.0	3 5	0 144	1
21140	Pressure-Burst Disk, 100 psi	0 6	0 833	1 0	1 5	0.2	1
21150	Lines and Fittings (40)	2 0	5 0	10 0	25 0	1.0	2
21170	Pressure-Burst Disk, 800 psi	0 6	0 833	1 0	1 5	0.2	1
21180	Flex lines	34 84	0 287	1 0	1 57	0.51	1
24010	Alternator	0 7	2 86	8 0	22.0	1 0	3
24020	Alternator Starter Winding	0.3	0 0	8 0	22.0	1 0	3
24030	Rectifier and Battery Charger	20 2	0 5	1 0	8 66	0 6	4
24040	Connector, 2-pin (Female)	0 4	0 0	10 0	25 0	1 0	4
26010	Throttle-Valve Control Circuit	83.3	0.356	1 0	7 5	0.2	4
26020	Burner Control and Ignition Logic Circuit	36.3	0.723	1.0	4.15	0 2	4
26030	Fuel-Rate Circuit	83 3	0 0	1.0	7 5	0.2	4
26040	Speed-Control Circuit Alternator	83 3	0 0	1 0	7 5	0 2	4
26050	Speed-Control Circuit, Condenser Fan	83 3	0 0	1 0	7 5	0 2	4
26060	Overpressure Shutdown Circuit	14 3	0 0	1 0	7.75	0 2	4
26070	Starting Logic Circuit	64.3	0 0	1	5 61	0 2	4
26080	Control Connecting Circuit	25.0	0 0	1.0	6 68	0 2	4
26090	Thermistor, Fuel Control	0 6	0 0	10 0	25 0	1.0	2
26110	Pressure Sensor, Condenser Fan Control	3 5	0 0	8 0	22 0	1 0	3
28010	Fuel Pump and Float Reservoir	29 24	0 676	1 0	2 5	0 2	1
28020	Fuel Pump Solenoid	5 38	0 0	1 0	2 5	0 2	1
28030	Fuel-Line Filter	0 3	0 0	10 0	25 0	1 0	2
28040	Burner	4 4	1 0	1 0	2 5	1 0	5
28050	Atomization Compressor and Motor	18 26	1 1	1 0	2 5	0 1	1
28060	Atomizer	10 1	0 0	1 0	1 0	0 1	1
28070	Combustion Air Blower	3 3	0 91	1 0	2 5	0 1	1
28080	Motor, Combustion Air Blower	2 35	0 0	1 0	2 5	0 1	1
28090	Igniters	3 62	0 0	1 0	6 0	0 05	1
28110	Condenser Fan	6 6	0 757	1 0	2 5	0 1	1
28120	Motor, Condenser Fan	4 21	0 0	1 0	2 5	0 1	1
28130	Motor Throttle Valve Driving	1 51	0 0	10 0	25 0	1 0	2
28140	Motor Starting Pump	20 2	0 0	1 0	1 5	0 5	1
28150	Battery	8 1	0 123	1 0	2 5	0 2	1
28160	Expansion Tank, Water Jacket	0 08	0 0	10 0	25 0	1 0	3
28170	Pressure-Burst Disk 2000 psi	0 6	0 833	1 0	1 5	0 2	1
28180	Fuel Lines and Connections	1 2	0 0	10 0	25 0	1 0	2
28190	Fuel Tank and Shutoff Valve	10 1	0 0	1 0	2 5	0 1	1
28210	Ducting	12 46	0 0	1 0	2 5	0 75	1
28220	Pressure Switch	7 87	0 172	1 0	2 5	0 1	1

n 55 (total number of components)

DATA SOURCE (1) FARADA
(2) Mechanical Design and Systems Handbook
(3) Apollo Reliability Prediction Estimation and Evaluations
(4) MIL-HDBK-217A
(5) Manufacturer

generator sets, more accurate values of mean time between failures than provided in this report should be obtained. It will be necessary to develop a data-collection and feedback system that will provide the proper historical information for improving design, lowering the cost of equipment repair, and reducing equipment downtime due to frequent failures.

4.2 DEVELOPMENT OF EQUIPMENT MAINTENANCE DATA

The information available for estimating component repair times is inadequate. Both manufacturers are planning systems with hermetically sealed organic-fluid loops; this will require that the generator set be transported back to a depot maintenance facility or the manufacturer for repair of any component that involves breaking this seal. The long-range development plans include making the systems repairable at the field maintenance facilities by providing the necessary loop-purging and fluid-charging equipment at that level.

The only equipments intended to be repairable by the user or support-level maintenance are system-support components and some of the power-generator components. The detailed design information concerning these areas is still being formulated by the manufacturers and is not yet adequate for developing realistic mean-time-to-repair (MTTR) values. However, STRATOS furnished a list of estimated repair times for the support components. The MTTR for organizational maintenance is 0.7 hour.

A detailed examination of system repairability should be made for each system, considering the present repair-level capabilities of both the prototyp models and anticipated production models. Repair times can be obtained at the same time prototype testing is being performed, and recommended design improvements can be reflected in those values.

With the proper data-collection and feedback program, the best reliability, maintainability, and availability figures can be obtained for the prototype designs and reasonably accurate estimates made for final production models.

CHAPTER FIVE

FAILURE MODE AND EFFECT ANALYSIS

The Failure Mode and Effect Analysis (FMEA) is an integral part of the reliability prediction. It is a systematic examination of all components of the system to identify their functions and how they can fail and to determine the effects of each component failure on the overall system in relation to mission performance and personnel safety.

The identification of problem areas can lead to design changes that improve reliability and maintainability or produce savings for the entire program. Based on FMEA results program management can adjust the test and evaluation programs to provide maximum assurance that the probability of critical failures has been either eliminated or reduced to a tolerable level.

In an FMEA, mathematical probabilities of occurrence are normally assigned to the various failure modes. For this report, the FMEA is presented primarily to permit a better understanding of the Rankine-cycle systems and the interaction of the components. No attempt is made to assign failure-mode probabilities, because of the lack of historical data on equipment of this type, and only the more prominent failure modes are listed. Since there is no inherent redundancy in the system, most of the component failures have the same ultimate effect on the system — loss of power output. Tables 3 and 4 are the FMEAs for the organic Rankine-cycle engine generator sets of Fairchild Hiller Stratos Division and Thermo Electron Corporation, respectively.

The following elements comprise the FMEA format used:

- Group Code Number — the numbers assigned to each component or circuit in the reliability block diagrams in Section 3.3
- Description of Component/Assembly — the nomenclature of the components or circuits as specified by each manufacturer
- Function — the general description of each FMEA component's functioning in the system
- Failure Mode — the type of failure judged to have a probability of occurring during a mission
- Failure Cause — the most probable causes of the failure
- Failure Effect — the effect of the failure on the system and the mission
- Criticality — the severity of each failure mode and its related failure effect on a discrete phase of the mission:
  - Critical (C) — a failure that prevents the component from completing a discrete phase of the mission or is judged hazardous to personnel

- - **Major (M)** — a failure that significantly degrades the performance of the component or delays its function such that it may not complete a discrete phase of the mission
  - **Minor (m)** — a failure that does not have a significant effect on the ability of the component to complete the discrete phase of the mission, but should be repaired eventually

- **Action Taken/Avoidance Technique** — the action to be taken by the user to return the set to operational condition; or the technique that can be used during manufacture to eliminate, or minimize the effect of, the failure mode or to make the set easier to repair in the field

Table 3. **FAILURE MODE AND EFFECT ANALYSIS FOR STRATOS ENGINE GENERATOR SET**

Group Code No	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
				FLUID LOOP-11000			
11010	Boiler	Convert the working fluid (FC 75) from a liquid to a vapor; contain and muffle the burner flame	Rupture in working-fluid tube	Overheating, fatigue, thermal expansion	Working fluid deterioration from overheating, causing corrosion in system components Loss of working fluid, causing system shutdown	M/C C	Safety devices will prevent system damage from overheating by shutting system down.
			Ruptured boiler casing	Hot start, fatigue, thermal expansion	System shutdown, excessive noise	C	
** 11030	Start Valve	Restrict fluid flow in the system at start up until the prescribed vapor pressure and temperature is reached	(1) Failure to close; (2) Failure to open; (3) Failure to open or close completely	Corrosion, erosion, clogging from contamination of working fluid; broken spring, bellows, or plunger	(1) Failure to close; system start-up will be delayed, possible damage to turbo-alternator pump (2) Failure to open; system shut down by safety over-temperature sensors (3) Failure to open close completely; system output reduced by flow restriction	m M C m,C	
11040	Modulation Valve	Control the flow rate of the working vapor to the turbine to maintain constant alternator RPM	Failure of valve to control flow	Valve frozen or jammed from contamination or corrosion Valve worn excessively from erosion, allowing excessive flow of vapor to turbine	Inability to regulate RPM and loss of output regulation	M/C	
11050	Turbo-alternator Pump (T-A P)	Contains a rotary engine (turbine) (1) on a rigid shaft with the alternator (2) which provides primary and accessory power and excitation for the field coils, and the feed pump (3) which increases the pressure of the working fluid prior to entering the boiler	(1) Failure of turbine	Misalignment from bearing or spacer wear, causing vibration or contact with nozzle	Deterioration of output until system shuts down	M C	
			(2) Failure of alternator - primary power, accessory power	Open, grounded, shorted winding	Primary: reduction or loss of output power — system continues to operate Accessory: loss of system	C C	
			(3) Failure of pump	Cavitation, wear, corrosion of pump blades, intake, or exhaust ports	Reduction in pumping capability, causing reduced system output to system shutdown		
			Cracked, broken, leaking housing	Fatigue, shock, vibration, manufacturer's defect	Loss of working fluid, causing deterioration of output to system low-pressure shutdown	M C	
11060	Regenerator assembly	Increase temperature of the working fluid before it enters the boiler by transfering heat from the working vapor after it leaves the engine	Housing rupture (vapor area) Finned-tube rupture (liquid area)	Fracture at flaw, or fatigue from vibration, shock, thermal expansion	Deterioration until system shuts down	C	
			Clogged fins on heat exchanger	Deposit buildup on fins from working-fluid contamination	Reduced efficiency	M	
11070	Mixing Section De-Super heater	Mix the fluid that has lubricated the T-A P bearings with the vapor before it enters the condenser	Ruptured housing; mixing section clogged, corroded, eroded	Fatigue, shock, vibration, contaminated working fluid, or thermal stress	Loss of working fluid, causing system shutdown; improper mixing or buildup of back pressure on bearing lube lines, causing overheating of bearings	C M C	
11080	Condenser	Convert the working fluid from a vapor to a liquid by removing heat	Leak, ruptured tube	Fatigue from shock, vibration, or flaw at weld	System shutdown	C	Quality control and testing to assure integrity of fabricated tubing, housing, and brazing.
			Clogged condenser tubes	Contamination from working fluid	Loss of output	m M	PM tests of working fluid should detect contamination before critical buildup can take place.
			Clogging of cooling-air fins	Atmospheric-particle contamination	Loss of output	m	PM includes periodic cleaning of condenser-core fin area.
** 11110	Check Valve, Main	Prevent reverse working-fluid flow at start-up	Failure to open	Broken spring; ball jammed in orifice; opening clogged, or seat eroded, preventing ball from seating	Open: system will shut down from overpressurization	C	
			Failure to close		Close: system will not start — possible damage to boiler or deterioration of working fluid from overheating	C	
11120	Check Valve, Start up	Prevent working-fluid reverse flow through the start pump during system operation	Failure to open	Broken spring; ball jammed in orifice; opening clogged; or seat eroded, preventing ball from seating	Open: system cannot be started	C	
			Failure to close		Close: reverse flow through start pump into condenser will reduce output and possibly cause system shutdown	M C	
11130	Pressure Regulator, Bearing Lubricator	Maintain a constant pressure flow of working fluid lubricant to the T-A-P bearings	Failure to regulate the pressure	Worn parts, clogged, cracked casing	Low pressure: worn out T-A P bearings = system shutdown High pressure: overlubrication of bearings, causing fluid flow into alternator, possible viscous drag	M C M C	Pressure gage between regulator and bearings will give visual check
11140 and 18150	Starting Fluid Pump and Motor	Provide initial fluid pressure and flow to start the Rankine cycle engine generator set	Reduction in pump output capacity	Worn motor brushes or pump motor bearings, or fluid leakage	Possible inability to start system	m,M	Motor should be user repairable.
			Failure to pump	Motor failure from open, shorted, or grounded circuit or magnetic-coupling failure	Failure to start	C	
			Pump cavitation	Reservoir malfunction	Failure to start	C	

*C = Critical, M = Major, m = Minor. **11020 and 11090 are combined with 11180

(continued)

Table 3. (continued)

Group Code No.	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
11150	Drains, T-A-P	Drain fluid that leaks into the alternator back into the fluid loop	Drains clogged	Contaminated working fluid	Alternator fills with fluid. Viscous drag causes loss of output until system shuts down	C	
11160	Cooling Coil, Alternator	Transfer excess heat from the alternator to the working fluid	Ruptured or clogged working-fluid tube	Fatigue, thermal stress, shock, vibration, or contaminated working fluid	Gradual loss of working fluid, causing eventual system shutdown	C	
11170	Cooling Coil, Power Conditioner	Transfer excess heat from the power conditioner to the working fluid	Ruptured or clogged working fluid tube	Fatigue, thermal stress, shock, vibration, or contaminated working fluid	Gradual loss of working fluid, causing eventual system shutdown	C	
11020, 11090, 11180	Thermistor Connections, Piping and Joints, and Bellows Tube	Connect the components in the fluid and allow for thermal expansion of the piping	Leak, rupture	Fatigue due to temperature, shock, vibration	Loss of working fluid, causing reduced output to system shutdown	m/C	Before the fluid loop is filled and sealed, a helium leak test should be performed to insure loop integrity.
11190	Pressure-Burst Disk	Safety device in fluid loop that ruptures to prevent excessive system over pressure if shutdown circuit fails	Fails below rated pressure	Manufacturing defect	Premature loss of system	C	Pressure-burst disks represent final safe system shutdown before some fluid-loop component is damaged.
			Fails at rated pressure	System overpressure-shutdown circuit fails, disk works as designed	Loss of system with no damage to components in fluid loop	C	System safety pressure shutdown must be calibrated with great care
			Fails above rated pressure	Manufacturing defect	Loss of system with possible serious component damage	C	
11210	Pressure-Relief Valve	Functions in conjunction with the start-up valve (11030) to allow fluid to act on the bellows at the preset pressure	Valve fails to close	Broken spring, ball jammed in orifice, opening clogged; or seat eroded, preventing ball from seating	Close: system start-up may be retarded, with possible damage to T-A-P	m/M	
			Valve fails to open		Open, system shutdown by safety overtemperature sensor		
				POWER GENERATION-14000			
14010	Voltage Regulator VR1	Receives power from PS2 and provides field-coil excitation for primary power circuits	Fails to regulate	Out of adjustment, regulator failure from thermal stress, shock, vibration	Output voltage out of specification to total loss of output	M C	Modular replacement concept for electrical electronic circuits will minimize downtime and make unit user-repairable.
14020	Voltage Regulator VR2	Receives power from PS2 and provides field-coil excitation for accessories alternator	Fails to regulate	Out of adjustment, regulator failure from thermal stress, shock, vibration	Accessories output voltage out specification to total loss of accessories power	M C	See 14010
14030	Voltage Regulator VR3	Receives power from PS2 and provides regulation of 15W output for battery charging	Fails to regulate	Out of adjustment, regulator failure from thermal stress, shock, vibration	Improper charging of battery; eventual loss of battery power and capability to start system	M C	See 14010
14040	Power Conditioning Circuit PS1	Three-phase, full-wave-rectifier bridge circuit converting primary ac to primary dc power output	Rectifier fails	Normal component failure — shock vibration, thermal stress	Reduction in, to loss of, primary power	M C	See 14010.
14050	Power Conditioning Circuit PS2	Converts accessory power output from ac to dc for accessories use and for voltage regulators VR1, VR2, and VR3	Rectifier fails	Normal component failure — shock, vibration, thermal stress	Loss of all power, system shutdown	C	See 14010
14060	Power Conditioning Circuit PS3	Converts ac accessories power to dc for operation of condenser fan motor	Rectifier fails	Normal component failure — shock, vibration, thermal stress	Condenser fan motor slows or stops running; depending on ambient temperature and load system, could sustain operation to total shutdown	m C	See 14010.
14070	Connector 2 pin	Connect Load to Generator Set	Connector pin breaks	Deterioration from environmental elements	Inability to connect load to set	m M	In emergency connector can be jumpered. Repairable by user
				ELECTRONIC CONTROL CIRCUITS-16000			
16010	Overvoltage Crowbar Circuit	Protect control circuits from overvoltage condition	Failure of circuit, open	Failure of circuit component from shock, vibration, thermal stress, or random component failure	Open: no effect unless circuit is needed, at which time control-circuit damage could result from overvoltage	m C	Press-to-test loop may be method of determining if circuit is available.
			Failure of circuit, shorted	Same as above	Shorted: will trip out circuit breaker, shutting system down	C	See 14010
16020	30-Second Timer Circuit	Begin operating the start pump and boiler blower fan during system start up in order to prime the boiler with fluid and purge it of fuel vapor prior to ignition	Failure of circuit	Same as above	System will not start	C	See 14010

(continued)

Table 3 (continued)

Group Code No.	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
16030 and 16140	Overtemperature Circuit	Shut down system if working-fluid temperature exceeds 700°F by shutting off fuel supply	False signal	Same as above	System will shut down	C	See 14010
			Failure to sense overtemperature condition		If safe shutdown is required and does not occur, system can be seriously damaged from overheating. Overspeed circuit (16080) should function first		
16010	3-Minute Timer Circuit	Pick up the start sequence from the 30-second timer circuit and provide the capability to start the system, coordinate all the machinery required for startup, remove machinery from loop on proper sequence of starting, and shut down on false start	Failure to control startup sequence	Electrical-component failure due to temperature, vibration, shock, or random circuit failure	Failure to start system	C	Module replacement of circuit would eliminate downtime and make system user-repairable
					Failure to sequence startup mode properly — no problem, to no system start, or danger to personnel from boiler explosion	m C	Safety devices should be located to prevent ignition when large amounts of unburned fuel have been injected into boiler
16050 and 16160	Air and Fuel rate Control Circuit	Sense working fluid temperature and determine the amount of air and fuel required to maintain the generator load and operate the combustion air fan and fuel pump to provide that amount	Loss of signal	Open control circuit	System shutdown or failure to start	C	See 14010
			Loss of control full open	Failure of one or more circuit components	Full open — high boiler temperature; system continues to operate at full load, otherwise overpressure will cause safety shutdown	m C	
			Loss of control, full closed		Full closed — system shutdown or failure to start		
16060 and 16150	Speed-Control Circuit, Condenser Fan	Sense working-fluid temperature at the condenser (11080) exhaust port, turning on the fan motor or increasing decreasing fan speed to maintain steady state flow	Failure of control circuit	Contamination and wear of the temperature sensor; open, short, grounded control circuit	Instability — loss of output regulation	M	See 14010
					Failure open — motor continues to operate; system runs at reduced efficiency	M	
					Failure closed — loss of fan cooling, temperature pressure rise causes safety shutdown of system		
16070	Speed Control Circuit Turbine	Sense the speed of the alternator and send a signal to the linear proportional solenoid, which moves the modulation valve to maintain constant RPM	Failure of control circuit	Open, shorted, grounded circuit due to failure of one or more circuit components	Loss of output regulation	M C	See 14010
16080	Overspeed Circuit, Turbine	Shut system down by cutting off fuel supply should turbine overspeed	Failure of control circuit to sense overspeed	Same as above	If overspeed condition occurs and the circuit does not function, the system runs until overtemperature shutdown occurs or feed-pump cavitation occurs, output voltage will be uncontrollable	C	Circuit characteristic may make it advantageous to incorporate the speed-control circuit with this circuit to improve system reliability
						C	See 14010
16090	Control Connecting Circuit	Interconnect the control circuits forming an interacting network to start, run, protect, and shutdown the generator set	Failure of control circuit	Circuit open, shorted, grounded from thermal stress, vibration, shock or normal life wearout	No immediate effect, to system shutdown or inability to start	m C	See 14010.
16110	Ultrasonic Atomizer Oscillator Circuit	Convert steady state dc into a pulsing circuit for the atomizer rod	Loss of signal output	Circuit component failure from thermal stress, vibration, shock or normal life wearout	Fuel not atomized into boiler, causing safety hazard and system shutdown	C	See 14010.
			Improper signal output	Deterioration of circuit component	Improper burning of fuel in boiler; deterioration to loss of combustion and system	M C	
16120	Ignition Circuit	Provide the signal and current to the ignitor	Ignition loss	Open control circuit	System shutdown or failure to start	C	See 14010
16130	Speed Control Linear Solenoid	Receive the signal from the speed control circuit (16070) and translate that into a linear motion to move modulation valve (11040)	Failure of solenoid	Open, shorted, grounded coil	Inability to control turbine speed	C	

**16140 is combined with 16030. 16150 is combined with 16060. 16160 is combined with 16050.

(continued)

Table 3. (continued)

Group Code No.	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
				SUPPORT COMPONENTS-18000			
18010 and 18020	Fuel Pump and Motor	Provide the proper quantity of fuel to the ultrasonic atomizer	Failure to supply fuel	Line clogged from contamination, broken fuel line from vibration, fatigue	System shutdown	C	Fuel-line filter should be incorporated into system
				Motor winding shorted, grounded, open; pump gears jammed			Fuel pump and motor should be designed for repair or replacement by user.
			Reduction in fuel supply	Line contamination	Loss of regulation of voltage output	M	
				Pump gears worn; motor/ pump bearings worn, binding			
18030	Ultrasonic Atomizer	Atomize the fuel into the boiler for proper, efficient combustion	Atomizer clogged	Dirt in fuel	Improper burning of fuel in boiler; deterioration to loss of combustion and system	M/C	Fuel filter should be added to system to remove dirt from fuel.
			Atomizer failure	Coil shorted, grounded, or open	Fuel not atomized into boiler, causing safety hazard and system shutdown	C	Atomizer is user-reparable.
18040 and 18050	Combustion Air Fan and Motor	Supply the combustion air to the boiler for complete combustion of the fuel	Motor failure	Worn out brushes, windings shorted/open from excessive ambient temperature	Reduction of combustion air pressure, causing a reduction in output to total loss of system	M/C	Fan and motor should be designed for repair or replacement by user.
18060	Igniter	Provide the spark to ignite the fuel in the boiler	Failure to ignite fuel	Spark plug opened, shorted, grounded (contamination) worn	System shutdown or failure to start	C	Clean or replace plug.
18070 and 18080	Condenser Fan and Motor	Force cooling air to flow across the core fins of the condenser	(1) Motor failure	Worn bearings, open or shorted winding, worn brushes	(1) Deterioration of output to system shutdown by safety if motor stops completely	M/C	
			(2) Fan failure	Worn bearings	(2) Increase in noise level with worn bearings		
18090	Ducting	Channel the intake air to the boiler and the exhaust from the boiler	Cracked or ruptured ducting	Shock, vibration, thermal stress	Intake reduced air flow to boiler; full power output may not be achievable	m/M	Ducting can be repaired or replaced by user.
					Exhaust: damage to components adjacent to duct personnel and fire hazard		
18110	Battery, 24 Volts	Provide 24 Vdc starting current and winterization warm-up prior to starting	Loss of charge	Breakage, loss of electrolyte; surface or internal short.	Winterization battery can be used to start system if available; if no outside starting source exists, the generator set cannot be started	M/C	System can be jumper-started by a standard 24 volt military truck battery
18120	Fuel Lines and Fittings	Conduct the fuel from the fuel tank to the fuel pump and then to the atomizer	Fuel line clogged, leaking, ruptured	Contamination in fuel, vibration, shock	Possible loss of output regulation at full load to total loss of system	m/C	Visual inspection should show leaks. Fuel line should be user-reparable
18130	Fuel-Line Filter	Filter contaminants from the fuel	Filter screen clogged	Contaminants in fuel	Reduction in output	m/M	Clean filter during regularly scheduled PM
18140	Fuel Tank and Shut Off Valve	Contain an eight-hour fuel supply	Tank leaking, cracked, ruptured; valve clogged, jammed, broken	Vibration, shock, thermal stress	Leaking fuel could cause fire hazard	m/C	Visual inspection should show leaks. Tank should be user replaceable.
					System should be shutdown for immediate repair		
*18150			Filter screen deteriorated, cracked, broken	Vibration, shock, fatigue	Clogged atomization burner, causing reduction in output to loss of system	m	Replace damaged filters during PM.

*18150 is combined with 11140.

Table 4 FAILURE MODE AND EFFECT ANALYSIS FOR TECO ENGINE GENERATOR SET							
Group Code No	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
				FLUID LOOP-21000			
21010	Boiler Coil, Jacket and Casing	Convert the working fluid (CP34) from a liquid to a vapor, separate the working fluid from the buffer fluid, and retain and muffle the burner flame	Rupture in working-fluid tube	Overheating, fatigue, thermal expansion	Working fluid deteriorated by mixing with buffer fluid, causing gradual reduction in output	M/C	Safety devices will prevent system damage due to over pressurization by shutting system down
			Rupture in buffer fluid tube	Overheating, fatigue, thermal expansion	Working fluid hot spots due to loss of buffer fluid, causing gradual reduction in output	M/C	
					System shutdown resulting from buffer fluid's extinguishing flame	C	
			Ruptured boiler casing	Hot start, fatigue, thermal expansion	System shutdown	C	
21030	Separator Assembly	Separate the silicone lubricant from the working fluid and return the lubricant to the engine crankcase	Collector screen clogged	Deposit buildup on screen from working-fluid contamination	Reduced efficiency	M	
			Collector screens cracked, broken	Fatigue, shock, vibration	Oil carried throughout the system, loss of lubricating function, slow progression to shutdown	M	
			Float valve fails full closed	Deposits and particles from fluid/oil contamination	Working fluid flows into crankcase — output falls off	M	
			Float valve fails full closed	Mechanical linkage broken, jammed, disconnected	Oil carried throughout the system, loss of lubricating function, rapid progression to shutdown	C	Placing sight glass on tank could give visual-inspection capability during operation.
			Float valve sticking	Particle contamination	Loss of system efficiency	M	
			Rupture or failure at joints	Fatigue, shock, vibration, thermal expansion	Deterioration to shutdown	C	Pressure gage should indicate fluid loss prior to shutdown
21040 and 25130	Throttle Valve and Driving Motor	Throttle the working fluid flow to control expander rpm	Valve sticking or leaking	Contamination in working fluid, rupture in O-ring	Deterioration in output regulation	M	
			No control	Drive motor open, shorted, grounded	Output deterioration to system shutdown	M/C	
			Bellows rupture	Fatigue due to vibration, shock, temperature, initial flow	System shutdown by over pressure safety	C	
21050	Expander Engine	Convert working vapor flow energy into rotational shaft motion to drive alternator	Wear of valves, bearings, and rings, metal fretting	Contaminated lubricant, natural mechanical wear due to age	Increase noise level, loss in energy-conversion efficiency	m/M	Increased noise indicates serious wearing of parts
			Leakage, static or dynamic	Wearing or failure of shaft rotary seals	Static leak results in influx of contaminants to the system, dynamic leak results in loss of working fluid, thus a drop in system output	M	Rate of fluid flow from reservoir will indicate system fluid-loop integrity Maximum requirements should be established prior to system-integrity testing
			Shaft bearing seizing and fracturing	Shaft bearing defect, wear, and fatigue	System shutdown	C	
			Housing rupture	Fatigue, defect of casting	System shutdown, loss of working fluid	C	
21060	Regenerator Assembly	Increase the working fluid's temperature before it enters the boiler by transferring heat from the working vapor after it leaves the engine	Housing rupture (vapor area) Finned-tube rupture	Fracture at flaw, or fatigue from vibration, shock, thermal expansion	Deterioration to system shutdown	C	Quality control and testing to assure integrity of fabricated tubing, housing, and brazing
			Clogged fins on heat exchanger	Deposit buildup on fins from working-fluid contamination	Reduced efficiency	M	
21070	Condenser	Convert the working vapor to a fluid by removing heat	Leak, ruptured tube	Fatigue from shock, vibration or flaw at weld	System shutdown	C	Quality control and testing to assure integrity of fabricated tubing, housing and brazing
			Clogged condenser tubes	Contamination from working fluid	Loss of output	m/M	PM tests of working fluid should detect contamination before critical buildup can take plac
			Clogging of cooling air fins	Atmospheric-particle contamination	Loss of output	m	PM includes periodic cleaning of condenser-core fin area
21080	Feed Pump	Raise the pressure of the working fluid before it enters the boiler	Worn valves, seals and bearings, fatigue in springs	Contaminated lubricant and working fluid, natural mechanical wear from age	Increased noise level, reduced output	m/M	
			Rupture — loss of working fluid or lubricant	Fatigue of housing fasteners and seals	System shutdown	C	
			Failure of pump to operate	Shaft fracture, piston seizing, or gear breakage due to flaw or fatigue and excessive wear from lube-oil failure	Complete loss of pressurization causing system shutdown	C	Increased noise indicates serious wearing of parts
21110	By Pass Valve	Bypass excessive fluid pressure from feed pump back to the condenser	Fail closed	Mechanical wear	Fail closed — pressure in boiler increases until safety pressure switches shut down system	C	
			Fail open		Fail open — condenser pressure increases		
			Rupture of housing	Fatigue from shock, vibration thermal stress, and/or flaw in manufacturing	Loss of working fluid causing system shutdown	C	

*C = Critical, M = Major, m = Minor **21020 and 21090 are combined with 21160

(continued)

Table 4 (continued)

Group Code No.	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
FLUID LOOP-21000 (continued)							
21120	Starting Fluid Control Reservoir	Provide a fluid reservoir for the start pump (21130) and the feed pump (20090) to prevent pump cavitation	Leaking, ruptured reservoir	Fatigue from vibration, shock	Loss of fluid, causing system shutdown	M/C	
			Float valve fails to operate	Mechanical linkage broken, jammed from erosion or deposits from contaminated fluid	Valve failed closed, system will not start		
					Valve failed open, reduction of system output	M/C	
21130 and 28140	Starting Fluid Pump and Motor	Provide initial fluid pressure and flow to start the Rankine cycle engine generator set	Reduction in pump output capacity	Worn motor brushes, pump motor bearings, or fluid leakage	Possible inability to start system	m/M	
					Loss of regulation of output	m/M	
			Failure to pump	Motor failure from open, shorted, or grounded circuit or magnetic coupling failure	Failure to start	C	
			Pump cavitation	Reservoir (21120) malfunction	Failure to start	C	
21140 21170 and 28170	Pressure Burst Disks 100, 800, 2000 psi	Safety device in fluid loop and buffer fluid line which ruptures to prevent excessive system overpressurization if safety-pressure shut down circuit fails	Fails below rated pressure	Manufacturing defect	Premature loss of system	C	Pressure-burst disks represent final safe system shutdown prior to damaging some fluid-loop component.
			Fails at rated pressure	System over-pressure shutdown circuit fails, disk works as designed	Loss of system with no damage to components in fluid loop	C	System safety pressure shutdown must be calibrated with great care.
			Fails above rated pressure	Manufacturing defect	Loss of system with possible serious component damage		
21020 21080 21150 and 21180	Thermistor and Pressure Sensor Connections, Lines and Fittings, and Flexlines	Connect the components in the fluid loop	Leak, rupture	Fatigue due to temperature, shock, vibration	Loss of working fluid, causing reduced output to system	M/C	Before the filling and sealing of the fluid loop, a static pressure test should be performed to ensure Loop integrity.
POWER GENERATION — 24000							
24010 and 24020	Alternator Starting Motor	Generate the output power of the system, provide internal power for sustained system operation, and act as a starting motor for the system feedpump at system startup	Deterioration to loss of a-c output voltage	Generator windings open, shorted, grounded; worn or open circuit in AC slip rings, bearing failure	Reduced voltage regulation to no system output	M/C	
			Loss of starting torque	D-c field circuit open, shorted, grounded	Progressive degradation resulting in inability to start		
24030	Rectifier and Battery Charging Circuit	Charge the battery after system startup	Failure of battery-charging circuit	Electronic-component failure due to temperature, shock, vibration, or random circuit failure	Spare battery can be used to start system if available but must be charged by other means. If there is no outside starting source, the generator set cannot be started.	M/C	System can be jumper-started with a standard 24-volt military battery
ELECTRONIC CONTROL CIRCUITS — 26000							
26010 26040	Speed Sensing and Throttle Valve Logic Circuit	Sense alternator (24010) frequency and load and adjust the throttle valve (21040 and 28130) to maintain constant RPM	Loss of signal. Fail full-open command. Fail full-closed command.	Electrical-component failure (catastrophic or drift) due to temperature, vibration, shock, or random circuit failure	Loss of signal. Full-open command — overspeed, loss of regulation, and ultimate system shutdown due to overpressure	M/C	Modular replacement of control circuit would minimize system downtime and make unit user-repairable.
					Full-closed command — Loss of regulation, slow speed, system shutdown due to overpressure	M/C	
			Instability — loss of control	Electronic-component deterioration	Instability — loss of output regulation	M	
26020	Burner Control and Ignition Logic Circuit	Provide the signal and current to the igniter and burner	Ignition loss	Open control circuit	System shutdown or failure to start	C	Modular replacement of control circuit would minimize system downtime and make unit user-repairable
			Loss of control, full open Loss of control, full closed	Failure of thermistor, relay, solenoids, or other circuit components, or combinations of these	Full open: high boiler temperature, system continues to operate if at full load; otherwise, overpressure will cause safety shutdown	M/C	
					Full closed: low boiler temperature; system inability to handle full load with required regulation		
26030 and 26090	Fuel Rate Logic Circuit	Determine the amount of fuel required to maintain the generator load and operate the fuel pump to provide that amount	Loss of signal	Open control circuit	System shutdown or failure to start	C	Modular replacement of control circuit would minimize system downtime and make unit user repairable
			Loss of control, full open Loss of control, full closed	Failure of one or more circuit components	Full open: high boiler temperature; system continues to operate at full load, otherwise, overpressure will cause safety shutdown	M/C	
					Full closed: system shutdown or failure to start		

(continued)

Table 4 (continued)

Group Code No	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken Avoidance Technique
				ELECTRONIC CONTROL CIRCUITS – 26000 (continued)			
26050 and 26110	Pressure-Control Condenser Fan Logic Circuit	Sense working fluid pressure at the condenser (21070) discharge, turning on off the fan motor or increasing decreasing fan speed to maintain steady-state pressure	Failure of control circuit	Contamination and wear of the pressure sensor, open, short, grounded control circuit	Instability loss of output regulation	M q	Modular replacement of control circuit would minimize system downtime and make unit user repairable
					Fail open motor continues to operate, system runs at reduced efficiency	m	
					Fail closed loss of fan cooling, temperature pressure rise causes safety shutdown of system	C	
26060	Overtemperature Circuit	Sense fluid temperature at boiler discharge and safety-shutdown the system by cutting off the fuel supply should temperature exceed preset limit	False-signal	Failure of circuit component or thermistor	System will shutdown	C	Modular replacement of control circuit would minimize system downtime and make unit user-repairable
			Failure to function on overtemperature	Improper setting, deterioration of thermistor	Pressure burst disc will actuate System will shutdown and be rendered useless	M C	Press-to-test capability should be installed if possible
26070	Starting Logic Circuit	Provide the capability to start the system, coordinate all the machinery required for start-up, remove machinery from loop on proper sequence of starting, and shutdown on false start	Failure to control start-up sequence	Electrical-component failure due to temperature, vibration, shock or random circuit failure	Fail''re to start system	C	Modular replacement of control circuit would minimize system downtime and make unit user-repairable.
					Failure to sequence startup mode properly – no problem to no system start or danger to personnel system from boiler explosion	M C	Safety devices should be located to prevent ignition when large amounts of unburned fuel have been injected into boiler
26080	Control Connecting Circuit	Interconnects the control circuits forming an interacting network to start run, protect, and shut down the generator set	Failure of circuit	Circuit open, shorted, grounded component failure from thermal stress, vibrations, shock or normal life wearout	No immediate effect to system shutdown or inability to start	m C	Modular replacement of control circuit would minimize system downtime and make unit user-repairable
				SUPPORT COMPONENTS – 28000			
28010 and 28020	Fuel Pump Float Reservoir and Solenoid	Provide the proper quantity of fuel to the atomization burner	Failure to supply fuel	Line clogged from contamination, broken fuel line from vibration fatigue, solenoid pump open circuit	System shutdown	C	Fuel-line filter checked and cleaned
			Reduction in fuel supply	Diaphragm-valve leak, line contamination	Loss of regulation of voltage output to solenoid	M	Fuel transfer pump should be designed for repair or replacement by user.
28030	Fuel Line Filter	Filter contaminants from the fuel	Filter screen clogged	Contaminants in fuel	Reduction in output	M-C	Clean filter during regularly scheduled PM
			Filter screen deteriorated, cracked, broken	Vibration, shock, fatigue	Clogged atomization burner causing reduction in output to loss of system	C	Replace damaged filters during PM
28040	Burner Assembly	Produce the flame to heat the working fluid	Poor combustion	Deterioration of burner parts from progressive oxidation	Gradual reduction in output	M	Preventive maintenance checks should detect deterioration before major problem occurs
				Poor fuel quality			Clean or replace fuel-line filter, drain and refill fuel tank
			Loss of fuel	Nozzle clogging, line contamination	System shutdown or failure to start	C	Clean fuel lines burner nozzle drain and refill fuel tank
28050	Atomization Compressor and Motor	Compress the air that is used to atomize the fuel and inject the mixture into the boiler	Ruptured diaphragm	Deterioration fatigue	System shutdown	[illegible]	Compressor and motor should be designed for repair or replacement by user
			Motor failure	Worn out brushes	Reduction in output	M C	
				Windings shorted open due to excessive ambient temperature	System shutdown	C	
28060	Atomizer	Reduce the fuel to fine particles in a spray for injection into the burner	Failure to atomize fuel properly	Clogged, worn by contaminants in fuel	Improper combustion in boiler, causing reduced output to loss of system	M C	Periodic cleaning of atomizer
28070 and 28080	Combustion Blower and Motor	Supply the combustion air to the boiler for complete combustion of the fuel	Motor failure	Worn out brushes, windings shorted-open due to excessive ambient temperature	Loss of air pressure, causing a reduction in output, burner flame would be sustained at reduced efficiency by atomization and available air	m M	Compressor and motor should be designed for repair or replacement by user
28090	Igniter	Provide the heat to ignite the fuel in the boiler	Loss of ignition	Glow-plug electrode opened, shorted, or grounded (contamination)	Failure to start	C	Clean or replace plug
28110 and 28120	Condenser Fan and Motor	[illegible]	Motor failure	Worn bearings, open or shorted winding worn brushes	Deterioration of output to system safety shutdown if motor is complete failure	m C	Fan and motor should be designed for repair or replacement by user
					Increase in noise level from worn bearings		
28150	Battery 12 Volts	[illegible] starting current	Loss of charge	Breakage loss of electrolyte Surface or internal short	Spare battery can be used to start system If no outside starting source exists, the generator set cannot be started	M C	System can be jumper started from a standard 24 volt military battery

** 28100 is combined with 26050 [illegible] is combined with 26050 28130 is combined with 21010 28140 is combined with 21130

(continued)

Table 4 (continued)

Group Code No.	Description of Component/ Assembly	Function	Failure Mode	Failure Cause	Failure Effect	Criticality*	Action Taken/ Avoidance Technique
SUPPORT COMPONENTS — 28000 (continued)							
28160	Expansion Tank Boiler Jacket	Act as a reservoir for the buffer fluid and provide an area for thermal expansion during boiler operation	Leaking or rupture in tank	Fatigue, vibration, shock, excessive thermal expansion	Loss of buffer fluid, gradual reduction in operation to system shutdown	M/C	Unit designed to withstand pressure temperature beyond the limit where the working-fluid/temperature pressure would cause system safety shutdown
** 28180	Fuel Lines and Connections	Conduct the fuel from the fuel tank to the atomizer through the fuel pump	Fuel Line clogged, leaking, ruptured	Contamination in fuel, vibration, shock	Possible loss of output regulation at full load to total loss of system	m/C	Visual inspection should show leaks. Fuel Line should be user-repairable.
28190	Fuel Tank and Shutoff Valve	Contain an eight-hour supply of fuel	Tank leaking, cracked, ruptured; valve clogged, jammed, broken	Vibration, shock, thermal stress, contaminated fuel	Leaking fuel could cause fire hazard. System should be shutdown for immediate repair	m/C	Visual inspection should show leaks. Tank should be user-repairable.
28210	Ducting	Channel the intake air to the boiler and the exhaust from the boiler	Cracked or ruptured	Shock, vibration, thermal stress	Intake: reduced air flow to boiler; full power output may not be achievable Exhaust — damage to components adjacent to ducting; personnel and fire hazard; increase in noise	m/M	Ducting can be repaired or replaced by user.
28220	Pressure switches	Shut system down if 100 psi or 2000 psi pressure burst discs rupture	Failure to function when burst disc ruptures Premature Failure	Manufacturing defect Open, shorted, or grounded circuit	Possible system damage from delayed shutdown Loss of system from false safety shutdown	m/M C	Incorporation of a press to test circuit may detect unsatisfactory switch.

**28170 is combined with 21140.

CHAPTER SIX

COMPUTER PROGRAM

The computer program was developed on a time-sharing system with basic FORTRAN used as the language. This made the program suitable for use on USAMERDC's COMSHARE time-sharing system with their preferred XTRAN language.

The program, described and illustrated in Appendix B, is designed to assess the reliability of a simple series system. It can assess individual component redundancy when the appropriate inputs are provided for the redundant elements. Four reliability or failure distributions can be manipulated in the program: the exponential, normal, lognormal, and probability distributions. It is not necessary for all components to have the same distribution, but one component cannot have two failure distributions at one time. The four individual K factors can be applied to the single component failure rate to account for different system environments.

Appendix B also presents detailed instructions for exercising the program on a time-sharing computer terminal.

CHAPTER SEVEN

RELIABILITY AND AVAILABILITY PREDICTIONS

7.1 RELIABILITY PREDICTIONS

Reliability-prediction models were developed to represent the organic Rankine-cycle engine generator sets of Fairchild Hiller/Stratos Division and Thermo Electron Corporation. From these models, a computer program was derived; it yielded quantitative reliability predictions for the two systems.

Table 5 shows the specific results of the computer program for the two manufacturers' generator sets, operating for the two specified missions in the three environments.

Table 5. RANKINE-SYSTEM PREDICTED RELIABILITY

K Factor	Mission 1		Mission 2	
	STRATOS	TECO	STRATOS	TECO
Manufacturer	0.9882	0.9941	0.9516	0.9757
Portable	0.9703	0.9766	0.8819	0.9061
Track Vehicle	0.8752	0.8990	0.5736	0.6415
Laboratory	0.9950	0.9948	0.9794	0.9787

It can be seen that the more severe the environment, the lower the probability that the generator set will achieve the stated mission. The manufacturers' estimates for their own system reliability are also included for comparison purposes. An examination of their data and the final results indicates that they assumed a fixed ground installation rather than one in which the Rankine system would be portable.

There is little significant difference in the system predicted reliabilities for either manufacturer for any given environment and mission. Operational analysis and accumulated failure data may yield different empirical results.

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7.2 AVAILABILITY PREDICTION

The goal is to achieve a system inherent availability of 98 percent for each of the Rankine-cycle generator sets. Inherent availability is based on active operating and repair time and is the probability that the system will operate satisfactorily when called upon.

Mathematically, it can be defined as

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where

A_i = Inherent availability

MTBF = Mean time between failures (hours)

MTTR = Mean time to repair (hours)

Since a large portion of the organic Rankine-cycle generator set will not be repairable at the organizational level of maintenance, the estimate of the steady-state inherent availability is calculated as follows:

$$A_{(t)} = \frac{\text{MTBF (repairable components)}}{\text{MTBF + MTTR (repairable components)}} \times R_t \text{ (nonrepairable components)}$$

Table 6 shows the results of the availability predictions for the portable ground environment (K_2) for the 24 hour mission only. The maintainability information needed to derive the inherent availability was not available at the time this report was prepared, except for the STRATOS MTTR estimate of 0.7 hour; the maximum specified downtime of three hours was therefore used to compare the impact of repair on both systems' availability.

Table 6. **ESTIMATED STEADY-STATE INHERENT AVAILABILITY**

MTTR Source	STRATOS		TECO	
	MTTR (Hours)	$A_{(t)}$	MTTR (Hours)	$A_{(t)}$
Manufacturer	0.7	0.9171	–	– –
Contract Goal	3.0	0.9709	3.0	0.9783

Because of the large number of nonrepairable components and the high MTBF for the repairable components, the availability prediction differs only slightly from the reliability prediction.

CHAPTER EIGHT

FLUIDIC-CONTROL APPLICATION

In the present concept the organic Rankine-cycle engine generator sets will be controlled with electronic circuits. Since electronic circuits can fail catastrophically, another method of system control is being investigated — the use of fluidic components that are powered by the organic fluid's vapor pressure. The investigation to date has considered only the electronic circuits proposed by the two manufacturers.

The critical question is whether fluidic circuits can completely take the place of electronic circuits in the generator set. It is possible, but it is also believed that complete fluidic control is not practical. Fluidic circuits cannot compete with electronics in response time. Electronic responses are in microseconds and fluidics in milliseconds. Fluidic circuits are also usually larger than their electronic counterparts.

Yet fluidics has some advantages over electronics in that the controls can be hermetically sealed in the fluid loop. Contamination would be minimized, and there would be no dust or atmospheric corrosion to affect relay contacts, open leads, or solder joints. There are few moving parts in a fluidic circuit, as there are in electronic relays or stepping switches. Vibration is not a problem since the fluidic circuits are stacked and then fusion-bonded, forming an extremely rugged device.

In the organic Rankine-cycle generator sets, the best areas for the fluidic circuits are those in which pressure, temperature, or speed is being sensed and being converted to motion to regulate flow. The circuits in the system that detect fluid pressure and convert it to an output signal to control the condenser-motor, fuel-pump, and blower-motor speeds are best left as electronic circuits. These are electrical-signal input and output circuits; present fluidic circuits are not as compact, and their response time is slower.

The reliability of fluidic circuits is still in the very early prediction stage. Very little operational information has been accumulated on the circuits because of their still-limited use. It is known that leaks and contamination are the most prevalent failure modes, and it is believed that fusion-bonding the fluidic circuit and hermetically sealing the unit into the Rankine fluid loop would virtually eliminate these failure modes.

With the organic Rankine-cycle generator sets in the development stage, it may be premature to consider fluidic circuits. Each engine manufacturer is still making design changes, fluid-loop conditions are being revised, and the exact method of system control is still unknown in some instances. The design and fabrication of a fluidic circuit in itself is a complex effort because of the many unknowns and the lack of off-the-shelf standardized components

The feasibility of fluidic circuits should definitely be investigated and tentative designs established for the use of fluidic controls on the generator sets. The actual incorporation of partial fluidic controls should take place only when the organic Rankine-cycle generator sets function properly and demonstrate their practicality for use as field mobile power sources.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this program was to provide USAMERDC with a quantitative appraisal of the predicted reliability of two organic Rankine-cycle engine generator systems. The tasks performed to meet this objective led to the following conclusions:

- The two manufacturers are constructing generator sets under different power requirements. Care should be exercised in making comparisons. The predictive results show little significant difference between the reliabilities of STRATOS's or TECO's Rankine systems.
- The electronic control circuits had extremely high failure rates and contributed heavily to system unreliability. TECO is still designing its control circuits; therefore, the STRATOS failure rates were used for the yet undesigned circuits. In this way, the impact is the same on both manufacturers. When TECO completes its design, the TECO model can be modified.
- The failure rates used in this project are estimates based on historical data from similar equipment. Until firm system failure data are developed, the results should not be considered empirical.
- The hermetically sealed fluid loops cause the major portion of the generator sets to be nonfield-repairable. This contributes heavily to system unavailability.

ARINC Research Corporation recommends the following courses of action based on the results of the analysis:

- Implement a data-collection and feedback procedure for MERDC and the manufacturer's testing program of the organic Rankine-cycle engine generator set.
- Perform a detailed design analysis of the Rankine systems to determine the best areas for design improvement, redundancy of components, and repairability to improve reliability, maintainability, and availability.
- Begin developing a life-cycle cost program to evaluate the proposed designs for portable field generator sets against those now in use. The evaluations should consider as a minimum initial production and procurement costs, operational costs, and the effects of repairability, logistics, reliability, and maintainability.
- Make a critical evaluation of fluidic circuits versus modular-replacement electronic circuits for the Rankine generator sets. The present estimates of control-circuit reliability may make fluidic circuits a wise choice.

APPENDIX A

SOURCES OF FAILURE-RATE DATA

APOLLO Reliability Prediction, Estimation, and Evaluation Guidelines, National Aeronautics and Space Administration, December 1963.

RADC-TR-114, Volumes I, II, and III, *Data Collection for Nonelectronic Reliability Handbook*, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York, June 1968.

Failure Information Notebook, Special Technical Report No. 32, ARINC Research Corporation, December 31, 1965.

Mechanical Design and System Handbook, Harold A. Rothbart, McGraw-Hill Book Company, New York, 1964.

MIL-HDBK-217A, *Reliability Stress and Failure Rate Data for Electronic Equipment*, Department of Defense, 1 December 1965.

Army, Navy, Air Force and NASA FARADA Failure Rate Data Program, Volumes 1, 2, 3, and 4, Naval Fleet Missile Systems Analysis and Evaluations Group, Corona, California.

APPENDIX B

COMPUTER PROGRAM FLOW CHART AND INSTRUCTIONS FOR USE

FLOW CHART

The flow chart for the computer program is presented in Figure B–1.

INSTRUCTIONS FOR USE ON TIME-SHARING COMPUTER TERMINAL

The steps described herein must be strictly adhered to for the program to function properly.

When a link with the time-sharing system is established, the first symbol seen after "RUN" is typed is an equal(=) sign. After the equal sign, type the number of components (N) in the system and the number of cycles of operation (M) (ten maximum). Each of these variables is allocated two places, and the data must be right-justified.

A second equal sign will then appear, and the M sets of times of operation must be typed. Each set consists of two times, a startup time and a run time, in units of hours. Each time is allocated five places; it must be typed with a decimal place and in such a way that none of the five-digit fields overlap.

The third and last equal sign will appear, and the K-factor codes (1 to 4) must then be punched for the M cycles of operation. These factors are used to adjust the failure rate and mean values. There must be K factors for both startup and run; each K factor is punched in an I2 format This ends the data entry at the keyboard at the time of execution.

The failure rates, means, accrued operating time, and K factors are stored as file and called "XRDATA" for Fairchild/Stratos and "YRDATA" for Thermo Electron. Before running the program (XMODEL), it is necessary to type the following line if the data file for Fairchild/Stratos is to be used: 90 READ ("XRDATA", 4) (ISP(I, 1), ISP(I, 2) IDST(I), (VAR(I, J), J = 1, 7), I = 1, N).

The term XRDATA must be changed to YRDATA if the Thermo Electron data file is used.

When the data are prepunched, the following format is used, where one line represents one component:

- Columns 1–5 contain a line number code. This is not used by the model program but is used to edit and update data entries.

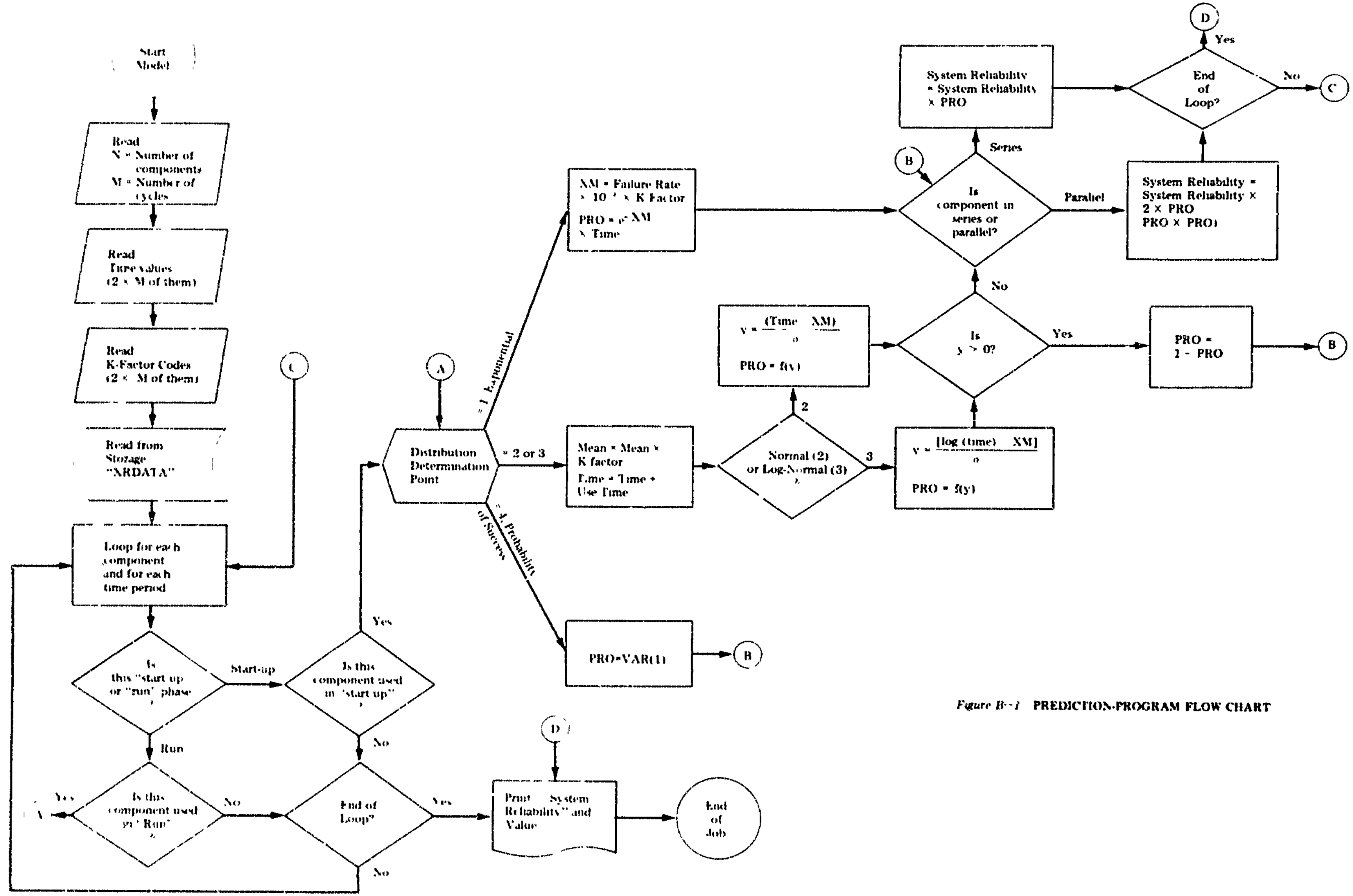

Figure B-1 **PREDICTION-PROGRAM FLOW CHART**

- Column 8 contains a "1" if the component is in series and a "2" if it is in parallel.
- Column 11 contains a "1" if the component is used in startup only, a "2" if it is used during run only, and a "3" if it is used for both phases.
- Column 14 contains the distribution codes:

  1 = exponential
  2 = normal
  3 = lognormal
  4 = probability of success

- Columns 15—21 contain the exponential failure rate $\times 10^6$, or the mean time to failure (normal or lognormal), or the probability of the component's success.
- Columns 22—28 contain the standard deviation (normal or lognormal) or are set to 0.
- Columns 29—35 contain the time the component has already operated if normal or lognormal is used or are otherwise set to 0.
- Columns 36—42 contain K factor number 1.
- Columns 43—49 contain K factor number 2.
- Columns 50—56 contain K factor number 3.
- Columns 57—63 contain K factor number 4.

Note 1: The last seven fields must be punched with a decimal point, and no fields may overlap.

Note 2: The values associated with lognormally distributed variables must be in terms of natural logarithms.

The prediction program is shown in Figure B—2.

```
DIMENSION ISP(75,2),IDST(75),VAR(75,7),T(20),IØP(20)
FILENAME FRDATA,XRDATA,YRDATA,ZRDATA
   READ 1,N,M
1 FORMAT(2I2)
   M=2*M
READ 2,(T(I),I=1,M)
2  FORMAT(10F5.0)
   READ 3,(IØP(I),I=1,M)
 3 FORMAT(20I2)
READ("YRDATA",4)(ISP(I,1),ISP(I,2),IDST(I),(VAR(I,J),J=1,7),I=1,N)
 4 FORMAT(5X,3I3,7F7.2)
PRINT:"PHASE AND SYSTEM RELIABILITIES, AND PHASE ØPER. TIME"
    S=1.0
    DO 10 J=1,M
    P=1.0
    XM=J
    XM=XM/2.0
    IM=XM
    DO 200 I=1,N
    IF(J-2*IM) 17,18,17
 17 IF(ISP(I,2)-2) 19,200,19
 18 IF(ISP(I,2)-2) 200,19,19
 19 IJ=IØP(J)+3
    II=IDST(I)
    GO TO (21,22,22,24),II
 21 XM=VAR(I,1)/1000000.0*VAR(I,IJ)
    PRO=(EXP(-XM*T(J)))
    GO TO 20
 22 XM=VAR(I,1)*VAR(I,IJ)
    TIME=T(J)+VAR(I,3)
    IF(II-2) 25,25,23
 25 Y=(TIME-XM)/VAR(I,2)
    GO TO 26
 23 Y=(ALOG(TIME)-XM)/VAR(I,2)
 26 PRO=0.5*(1.0+(1.0-EXP(-0.63662*Y*Y))**0.5)
    IF(Y) 20,20,28
 28 PRO=1.0-PRO

    GØ TØ 20
 24 PRO=VAR(I,1)
 20 IF(ISP(I,1)-1) 27,27,29
 27 P=P*PRO
    GO TØ 200
 29 P=P*(2.0*PRO-PRØ*PRØ)
200 CONTINUE
    S=S*P
    PRINT 9, P,S,T(J)
  9 FØRMAT(3E15.8)
 10 CØNTINUE
    PRINT: "SYSTEM RELIABILITY"
    PRINT 8,S
  8 FORMAT(E15.8)
    STØP
    END
```

Figure B—2. **PREDICTION PROGRAM**